STUDIES IN WIRELESS HOME NETWORKING INCLUDING COEXISTENCE OF UWB AND IEEE 802.11A SYSTEMS

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Babak Firoozbakhsh

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Studies in Wireless Home Networking Including Coexistence of UWB and IEEE 802.11a Systems

Approved by:

Professor Nikil Jayant, Advisor
School of Electrical and Computer Engineering
Georgia Institute of Technology

Professor David Anderson
School of Electrical and Computer Engineering
Georgia Institute of Technology

Professor John Copeland
School of Electrical and Computer Engineering
Georgia Institute of Technology

Dr. Thomas Pratt
Georgia Tech Research Institute
Georgia Institute of Technology

Professor Raghupathy Sivakumar
School of Electrical and Computer Engineering
Georgia Institute of Technology

Date Approved: January 10, 2007

To my loving father, mother, sister, and fiancée.

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SUMMARY

Characteristics of wireless home and office services and the corresponding networking issues are discussed. Local Area Networking (LAN) and Personal Area Networking (PAN) technologies such as IEEE 802.11 and Ultra Wideband (UWB) are introduced. IEEE 802.11a and UWB systems are susceptible to interference from each other due to their overlapping frequencies. The major contribution of this work is to provide a framework for coexistence of the two systems. The interference between the two systems is evaluated theoretically by developing analytical models, and by simulations. It is shown that the interference from UWB on IEEE 802.11a systems is generally insignificant. IEEE 802.11a interference on UWB systems, however, is very critical and can significantly increase the bit error rate (BER) and degrade the throughput of the UWB system. A novel idea in the MAC layer is presented to mitigate this interference by means of temporal separation. Simulation results validate our technique. Implications to wireless home services such as high definition television (HDTV) are provided. Future research directions are discussed.

CHAPTER I

INTRODUCTION

In recent years, there has been a lot of interest in wireless local area networks (LANs) in order to connect the many devices inside the home or in the office. Ideally, the devices can join the network in a plug and play fashion and can easily move around. Home and office wireless LANs pose many unique challenges. They have to support a large number of applications with different characteristics and different needs. The Quality of Service (QoS) requirements range from high delay and low bandwidth to low delay and high bandwidth communications. In addition, these networks must be scalable, flexible, safe, secure, easy to use, inexpensive, and power efficient.

Careful studies of existing technologies [5] demonstrate that none of the current standards by itself can answer all the needs of the future home. Ultra Wideband [6] is a superior technology with many applications for future wireless LANs and may complement the already popular IEEE 802.11 [7] technologies. UWB has potential for high data rates at very low power transmissions with resistance to multipath, and great indoor localization capabilities. Nonetheless, there may be interference between UWB and IEEE 802.11a [8] technologies in the home due to the overlapping of their frequency spectra. We study the coexistence of UWB and IEEE 802.11a technologies theoretically and develop useful analytical models. We also address the coexistence of IEEE 802.11 and UWB in the medium access control (MAC) layer and propose a solution to mitigate the interference between these technologies. Wireless LAN applications are not limited to computing and entertainment and are finding their way into every aspect of our lives. An example of this is presented in Appendix 1, where we monitor vital human signs over an IEEE 802.11 wireless LAN in real time.

This work examines UWB communications over wireless home/office networks, addressing a wide range of issues, such as the feasibility of UWB in the home/office with regard to interference, an innovative technique to mitigate this interference in the MAC layer, and an overview of different wireless home applications using different technologies/standards. The concentration of our research is demonstrated by Figure 1, focusing on the overlap of home/office wireless LAN with UWB and IEEE 802.11 technologies,and spanning several layers (e.g., physical and MAC) of the OSI network model.

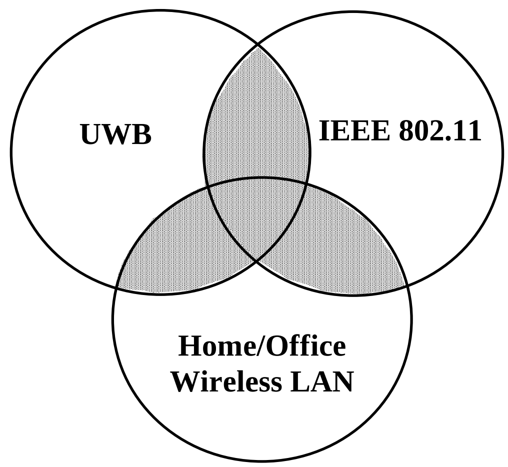


Figure 1: Proposed Research Concentration

This Thesis is organized as follows. Some background information regarding wireless home networking and UWB is presented in Chapter 2. In Chapter 3 we discuss the interference between UWB and IEEE 802.11a in the physical layer. More specifically, the asymmetry of interference between the two systems is discussed in section 3.1; section 3.2 evaluates the interference of UWB on IEEE 802.11a systems; and section 3.3 evaluates the interference of IEEE 802.11a systems on UWB systems in great detail. A novel technique to mitigate the interference in the MAC layer is presented in Chapter 4. This technique is simulated extensively in Chapter 4 and comparisons are made. Chapter 5 discusses wireless home applications and characteristics in more detail, and addresses UWB and 802.11a technologies and their coexistence, from an application-driven point of view, closing the loop between chapters 2, 3, and 4. Finally, concluding remarks and future research directions are presented in Chapter 6. Some additional research work, including our work on transmission of vital signs using the Georgia Tech Wearable Motherboard (GTWM) are presented in the Appendices.

CHAPTER II

BACKGROUND

Wireless home/office networks include wireless LANs and wireless personal area networks (PANs) within home and office environments. We use the terms wireless home, wireless office, and wireless home/office (WH/O) interchangeably to reflect wireless home and office networks collectively, since a wireless home can include a wireless home office as one of its many applications. We have based our research on a merger of new technologies and application in the wireless home. A typical wireless home is shown in Figure 2. The figure demonstrates some of the desired applications within the wireless home of the future. For example, the microwave can send a message to the palm pilot, informing the tenant that his/her meal is ready, and the vital signs of a person in critical conditions can be monitored continuously and transmitted to a hospital in case of an emergency. Most wireless home applications can be categorized as [9]:

- ***Home Automation and Inventory Control***: These applications involve controlling the local

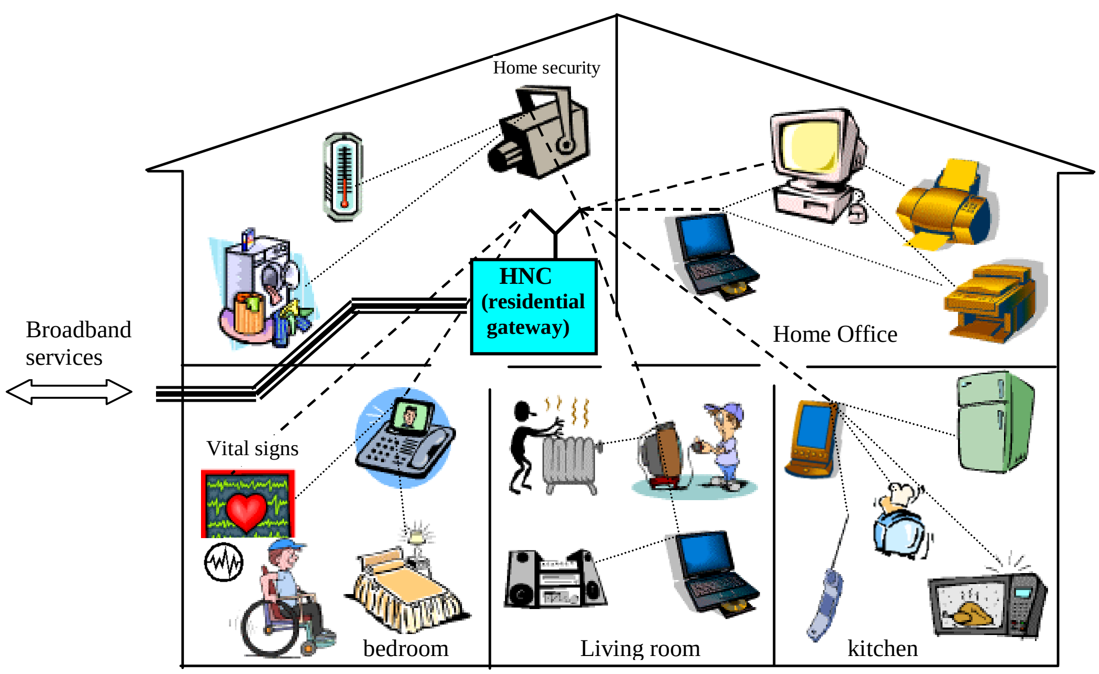


Figure 2: A Typical Wireless Home Network

environments and consist mainly of sensors and actuators. Examples include: automatic temperature control, home security, energy management, and inventory control.

- ***Entertainment Systems***: These include video on demand, audio, video, home theater, interactive games, etc. This group of applications perhaps demands the highest bandwidth.
- ***Home Data Networks***: These applications mainly consist of small-scale LANs and Personal Area Networks (PANs) for interconnecting products such as PCs, fax machines, palm pilots, and printers.
- ***Telephony***: Traditional telephony as well as applications such as videophones, etc.
- ***Telemedicine***: Although neglected in most publications, this will be a very important application in the future home. Examples include remote monitoring of patients, automated emergency calls, and remote contact with health-care professionals.

Most home environments will consist of passive and active information devices, as well as a residential gateway (Figure 2). Passive information devices collect information about the parameters they are monitoring but don't transmit them until polled by another device. Active information devices communicate with each other and with the residential gateway. The residential gateway, also called the Home Network Controller (HNC), is the interface between the home and the external world.

Within the wireless home, most likely a combination of centralized and distributed networks will exist. Some devices will communicate directly with one another with no pre-existing infrastructure, in a distributed (ad-hoc) fashion. Other devices will communicate in a centralized fashion, through a central node or base station.

2.1 Wireless Home Service Characteristics

2.1.1 Bandwidth Requirements

The traffic from the residential gateway to the end-terminals is called *downstream/downlink* traffic, whereas the traffic from the end terminals is called *upstream/uplink* traffic. Applications with similar characteristics (i.e., bandwidth) in each direction are referred to as being *symmetric*, where as those with distinct characteristics in each direction are referred to as being *asymmetric*. Many applications such as video games and interactive TV require large amount of data downstream and only a few bits upstream. Therefore, typically, most residential multimedia applications are asymmetric in that a much larger bandwidth is required for downstream transmission than upstream transmission. Table 1 provides an overview of some residential services and their bandwidth requirements [10,11]. A more detailed overview of audio, image, and video compression standards and their associated bit rates is given in chapter 5. A typical house requiring a few audio and video streams and some bandwidth for data transmission and interactive TV may require an aggregate bandwidth in excess of 100 Mbps.

Table 1: Bandwidth Requirements of Some Residential Services

Type of Service	Downstream	Upstream
Voice telephony	8-64 kb/s	8-64 kb/s
Telemetry surveillance	A few kb/s	0.1-10 Mb/s
CD-quality stereo (10 Hz-20kHz)	256 kb/s	–
Video conferencing	0.384-2 Mb/s	0.384-2 Mb/s
Data transfer, telecommuting	1-3 Mb/s	1-3 Mb/s
E-shopping	1.5-6 Mb/s	A few kb/s
Tele-education	1.5-3 Mb/s	16-64 kb/s
Video games, virtual reality	1-2 Mb/s	16-64 kb/s
Video on demand, Interactive TV		
MPEG1	1-2 Mb/s	A few kb/s
MPEG2 SDTV	3 Mb/s	A few kb/s
MPEG4 HDTV	8 Mb/s	A few kb/s

2.1.2 Delay Characteristics

Media applications in the home can be classified according to their delay requirements into several classes [1]:

- ***Non-real-time***: applications that don't carry any time-sensitive information. This group has the loosest latency constraints since the entire media can be downloaded before retrieving/ playback occurs. Electronic mail, voice mail, and downloading of images and pre-encoded audio are examples of this class.

- ***(Real-time) streaming***: applications that require almost simultaneous delivery and play back of the media, delivering time-based information over the network at the same rate as its source. In these applications, the media can be broken into pieces/blocks, which are transmitted in succession. The playback at the receiver begins before the entire media has downloaded. examples include real-time playing of audio and video over the internet, high definition TV, etc.

- ***(Real-time) Low latency communication***: Low latency applications are the most stringent/strict in terms of delay. Examples include conversational and some interactive applications such as voice over IP (VoIP), videophone/video conferencing, and interactive games. In low latency communication the goal is to minimize the latency as much as possible, and latencies above 100 to 200 msec may make the application unacceptable.

2.1.3 QoS Requirements

Quality of Service (QoS) is a vague term used to mean that the network provides some type of delivery or performance guarantees (e.g., guarantees of maximum error rate, bit rate, or delay). On the other hand, networks that simply provide network connectivity without specific guarantees of packet delivery or performance are usually referred to as *best-effort*. Among many other requirements, QoS considerations for multimedia applications include latency, jitter, error, and data/bit rate [11]:

- ***Latency*** refers to the absolute delay in arrival of the data and applies mainly to real-time (i.e., streaming and low latency) applications. The end-to-end latency depends on processing, packetization, transmission, queuing, and propagation delays.

- ***Delay variation (jitter)*** affects streaming and low-latency applications. This QoS requirement arises from the continuous traffic characteristic of such applications. Each set of data is generated continuously at regular instants and must be delivered within a bounded interval. Late arrivals result in receiver buffer underflow and cause breaks in the reception of the stream. Early arrivals lead to buffer overflow. Jitter requirements also arise from the need to synchronize between different media streams, such as audio and video in videoconferencing applications.

- ***Loss*** requirements apply to all classes of applications, since the main purpose of telecommunications is correct delivery of information. Most real-time applications (except for some medical applications or interactive data) tolerate a limited amount of data loss, depending on the error resiliency of the decoder. Conversely, non-real-time applications typically do not tolerate any loss at the application level.

- ***Data Rate*** or bit rate, is used to indicate the ”speed” of the network or the amount of data that is transmitted or received per unit of time. Some applications, such as checking email, are possible with networks that support relatively low bit rates. On the other hand, some applications that involve media, such as audio and video, are generally not possible, or quite unpleasant to use, over networks that only support low bit rates.

Sensitivity to delay (latency and jitter) and loss for some multimedia applications are provided in Table 2.

2.2 Wireless Home Network Design Issues

2.2.1 Unique Challenges

The wireless home is an environment where a number of devices with different services and different requirements coexist. The network must be able to provide connection among these devices

Table 2: Multimedia Sensitivity to Loss and Delay

Multimedia	Sensitivity to		Data Rate	Example	Application Class
	Loss	Delay			
Interactive Video	Small	Large	High	Video Conference	Low latency
Still image	Large	Small	Low	Picture in the Web	Non-real-time
Interactive Voice	Small	Large	Medium	Telephone	Low latency
Recorded music download	Small	Small	Medium	Voice on the Web	Streaming
Interactive Data -High speed -Low speed	 Large Large	 Large Medium	 High Low	 Real-time control Telnet	Streaming
Non-Interactive Data	Large	Small	Low	E-mail	Non-real-time
Telemedicine	Large	Large	Varies	Vital Signs Monitoring	Streaming

and also provide interfaces to external services/devices. The QoS requirements vary largely, but the overall network demands capabilities for high speed, high bandwidth communications with support for delay-sensitive and loss-sensitive applications. Moreover, some applications such as medical emergencies may have higher urgencies and priorities. Although some medical signals may not demand a high bandwidth, they require a great amount of reliability and redundancy. All protocols must be highly scalable and flexible and allow different data rates, different traffic classes, and different priorities in an optimal way.

Each application performs best under a certain network *topology*. The network must be highly *flexible* to support different topologies and to be able to coexist with other home networks. Moreover, the network must support high-speeds with rate-*scalability* in order to accommodate the highly dynamic home environment.

Another design consideration is *power*. Desirably, wireless devices should be easy to carry (limiting the battery size) and not tied down to a specific power source. Therefore, wireless standards and protocols should be designed to conserve power and extend the battery life as much as possible.

Safety is also an important design consideration. Since the inhabitants of the home are in constant exposure to the wireless network, we have to make sure that there are no possible harms from exposure to RF radiations. Low-power technologies are highly desirable and the amounts of RF radiation must be regulated.

Another important issue is the *security* of information and preservation of the *privacy* of the users. Security is usually achieved through encryption as well as the wireless technologies that offer inherent security, such as spread spectrum technologies.

Finally, consumer devices must be *inexpensive* and also easy to operate. Therefore, the system should be relatively simple and of *low complexity* in order to control the cost, yet it must be *easy* to install and use in a plug and play fashion.

In addition to the aforementioned issues, wireless home/office networks are subject to other challenges of indoor wireless communication. A detailed overview of these factors are presented in [5].

2.2.2 Additional Physical Layer Issues

Multipath: *Multipath* refers to interference caused by signals bouncing off of walls and other barriers and arriving at the receiver from different paths, different angles, and at different times (Figure 3). When the waves of multipath signals are out of phase, reduction in signal strength can occur; this creates rapid fluctuations in signal strength. Because multiple reflections of the transmitted signal may arrive at the receiver at different times, *inter-symbol interference* (ISI) may occur. This time dispersion of the channel is called *delay spread*.

Bursty Channel Errors: Because of it's time varying nature and interference, wireless channels are subject to relatively large errors. In contrast to wired networks where the errors are a result of random noise, wireless channels experience errors in long bursts. Wireless channels may have bit-error rates as high as 10-3 or higher, as compared to bit error rates of less than 10-6 in wireline networks [9].

Spread Spectrum Technologies:

To reduce narrow-band interference and mitigate multipath, spread spectrum techniques such as *frequency hopping spread spectrum* (FHSS) and *direct sequence spread spectrum* (DSSS) are widely used. Spread Spectrum (SS) "spreads" the signal power over a wider band of frequencies resulting in less interference from narrow band signals. Spread spectrum technologies provide higher data rates, more interference immunity, and lower interference generation compared to narrow band techniques. SS also provides nominal security by making it difficult to read the signal unless the specific spread code is known. These advantages have led most wireless LANs to implement spread spectrum techniques.

In the FHSS technique, the data signal is modulated with a carrier signal that hops from frequency to frequency as a function of time over a wide band of frequencies. FHSS reduces interference because an interfering signal will affect the SS signal only if both are transmitting at the same frequency at the same time. Using a set of orthogonal hopping codes, radio transmitters can use SS within the same frequency band and not interfere.

In the DSSS technique, the data signal is combined with a higher data rate bit sequence, referred

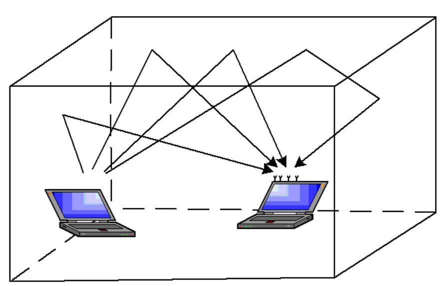


Figure 3: The Multipath Effect

to as the chipping code. A high processing gain increases the signal's resistance to interference. Using a set of orthogonal spreading codes, radio transmitters can use SS within the same frequency band and not interfere.

The choice of the spread spectrum technique depends on application requirements of the wireless LAN. Compared to DSSS, FHSS offers lower cost, lower power consumption, and higher tolerance to signal interference. DSSS in turn offers higher data rates from individual physical layers, and higher ranges of coverage. In most cases FHSS is the most cost-effective type of wireless LAN if the network bandwidth is 2 Mbps or less. DSSS, having higher potential data rates, is better suited for more bandwidth-intensive applications [12, 13].

Antenna Systems: Antenna systems play an important role in wireless telecommunications and in dealing with multipath. They can improve the performance of the system by exploiting space, angle, and polarization diversities. *Space diversity* is achieved by using multiple receiver antennas. The distance between the antennas is chosen to ensure uncorrelated (independent) fading; a space separation of half the wavelength will suffice. *Angle diversity* uses several directional antennas; each antenna will isolate a different angular component, so that uncorrelated signals are achieved [14]. *Polarization diversity* is a special case of space diversity with only two orthogonal diversity branches; if both horizontal- and vertical- polarized waves are transmitted simultaneously, uncorrelated fading can be achieved. Smart antennas can be used to increase the capacity of the wireless link through diversity gain, array gain and interference suppression. They consist of multiple antenna elements with a signal-processing capability to optimize the radiation and/or reception pattern automatically in response to the signal environment [15].

Wireless Modems: Design of *wireless modems* is more complex than wireline modems. In particular, wireless modems have to handle characteristics of wireless channels like *multipath*, *channel noise*, and *interference*, which significantly increase the complexity of implementation of wireless modems. To handle these characteristics, the wireless modems use robust modulation schemes like Frequency Shift Keying (FSK), Differential Phase Shift Keying (DPSK), Gaussian Minimum Shift Keying (GMSK) and Orthogonal Frequency Division Multiplexing (OFDM). Also, to mitigate multipath, spread spectrum technologies are widely used. The choice of a modulation is based on maximizing bandwidth efficiency (measured in bits/s/Hz) while using minimum battery power to achieve a certain prescribed bit error probability.

2.2.3 Additional Higher/MAC Layer Issues

Home Network Architecture Most home environments will consist of passive and active information devices, as well as a residential gateway (Figure 2). Passive information devices collect information about the parameters they are monitoring, but don't transmit them until polled by another device. Active information devices communicate with each other, and some communicate directly with the residential gateway [9]. The residential gateway, also called the Home Network Controller (HNC), is the interface between the home and the external world. All traffic to and from the home will have to pass through the HNC. It collects information from different devices, communicates with the outside world, and monitors the traffic for security reasons.

Centralized Vs. Distributed Wireless LANs: Wireless LANs can be categorized into two major groups: centralized and distributed.

In *centralized* wireless networks, a central node, referred to as the base station, is in charge of central administration (Figure 4a). The base station not only acts as the interface between the wireless terminals, but can also serve as an interface between the wireless and wireline network. In these networks, downstream transmissions are broadcast. The upstream channel is shared by all wireless terminals, and is therefore a multiple access channel.

A *distributed (ad-hoc)* network consists of wireless terminals communicating directly with one another, with no pre-existing infrastructure (Figure 4b). There is no base station to provide connectivity to the backbone or to other hosts. Because there is no backbone or infrastructure, the network can be formed or deformed immediately, on the fly. Moreover, the network doesn't collapse when one of the terminals (i.e. the base station) is shut down or moves away [16].

Collision Avoidance vs. Collision Detection: Collision detection is not used in wireless LAN/PAN environments because of the following reasons: (1) it is very difficult to transmit and receive on the same channel using radio transceivers since some of the transmitted signal may leak into the receive path, causing self-interference. (2) In wireless environment, not all stations can hear each other (the basic assumption of collision detection), due to hidden stations and fading. As a result, collision may still occur when the channel is sensed clear [17]. Therefore, collision avoidance (CA) is usually used instead. The collision avoidance technique is discussed in great detail in the following sections.

Hidden Nodes: A hidden node is a node that is within the range of the receiver, but out of the range of the sender. Hidden nodes can cause collision in data transmission. Consider the case shown in Figure 5: Station A is transmitting to station B. Station C cannot hear the transmission from A, so it falsely assumes the channel is idle and starts transmission, which interferes with the reception at B.

Exposed Nodes: An exposed node is a node that is within the range of the sender, but out of the range of the destination. In Figure 5 consider the case when node B is transmitting to node A. Node C hears the transmission and it thinks the channel is busy. However, it could be having a parallel conversation with another terminal out of range of B, without interfering with reception at node A. Too many exposed nodes can underutilize the bandwidth [9].

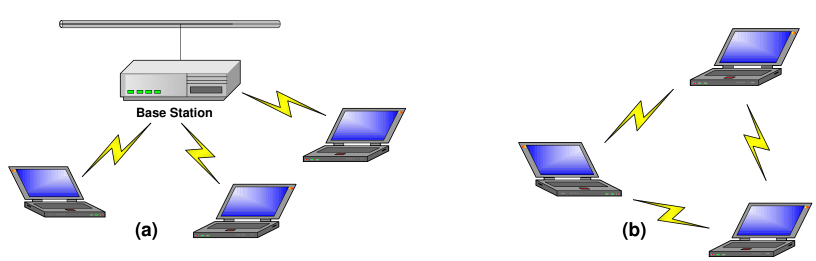


Figure 4: (a) Centralized network, (b) Distributed (ad-hoc) network

2.3 *Wireless MAC Protocols*

In a wireless medium, where multiple devices share the same resources or can access the medium at the same time, we need the means to moderate the access to the shared medium in an efficient and fair manner. MAC is a mechanism at the data link layer (OSI Layer 2) of communication networks that manages the access to the communication channel.

Wireless MAC protocols can be broadly classified into two categories: centralized and distributed (ad hoc). Centralized protocols can be further classified into three groups: guaranteed access protocols, random access protocols, and hybrid access protocols. Distributed protocols mainly use random access methods. Gummalla provides a good comparison of these protocols in [18].

2.3.1 Centralized MAC protocols

In guaranteed access mechanisms, the nodes access the channel in an orderly fashion, such as in a round-robin fashion [19, 20], often through polling by the base station. A main purpose of this class of protocols is to minimize idle periods during which the bandwidth is not used. Examples of guaranteed access mechanisms include Zhang's [19] round robin mechanism based on poll-request-poll-data handshaking, and disposable token MAC protocol (DTMP) [20] using just the poll-data cycle between the base station (BS) and other stations.

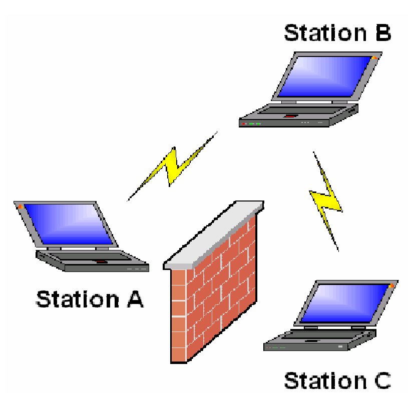


Figure 5: Hidden- and Exposed- Nodes

In random access protocols, nodes contend for access to the medium. Examples of centralized random access protocols include idle sense multiple access (ISMA) [21], randomly addressed polling (RAP) [22], and resource auction multiple access (RAMA) [23].

In ISMA [21], the BS senses the channel and if the medium is idle, it broadcasts an idle signal (IS). All nodes that have data to send, transmit with a specific probability. If the transmission is successful, the BS broadcasts an idle signal with an acknowledgement (ISA) for the next idle period. Otherwise, it transmits an IS. Improvements to ISMA include reservation ISMA [24] and slotted ISMA [25].

In RAP [22], each station chooses a pseudo-random number (code) from a number of orthogonal codes. All stations transmit their code simultaneously. The receiver uses a CDMA receiver to decode all the codes sent during the contention phase. It then polls for each code that was received, in an orderly manner. All nodes that picked a specific code will transmit after that code is polled, which can lead to collision if more than one station chose that code. If the transmission is successful, the BS responds with an acknowledgement (Ack). After all received codes are polled, a new contention phase begins.

In RAMA [23], each station transmits its b-bit ID symbol-by-symbol during the contention phase. The BS broadcasts the symbol it heard to all nodes. If this symbol doesn't match the one the station transmitted, it drops out. Since the channel performs an OR operation between the symbols, after b rounds the station with the highest ID wins the contention and transmits its data. This is unfair since the station with the highest ID will always win. Fair RAMA (F-RAMA) [26] tries to fix this by having the BS select one of the received symbols randomly. However, it does not explain how the BS can distinguish between the different symbols transmitted simultaneously.

Hybrid access protocols are a combination of random access and guaranteed-access schemes. Most hybrid access protocols are based on request-grant mechanisms [18]. Each node that wants to transmit, sends a request to the base station using a random access protocol. The base station then allocates uplink time slots for the data transmission of the requesting station(s) and informs the station(s).

2.3.2 Distributed MAC protocols

Distributed MAC protocols mainly use random access methods. Aloha [27, 28] and slotted Aloha (S-Aloha) [29] are the earliest examples of distributed random access protocols. Basically, any node that has data to send transmits it. If there's a collision, the node will back off for a random period of time and then tries again.

Most distributed MAC protocols employ carrier sense multiple access (CSMA) with collision avoidance (CA), collectively referred to as CSMA/CA. The basic operation of CSMA is as follows: If a station wants to transmit, it first senses the channel for a certain duration of time. If the channel is busy, it backs off for a random period before sensing the channel again. If the channel is idle, it tries to acquire the channel (for example through RTS-CTS handshaking below) after which it can transmit its data.

Examples of collision avoidance techniques include the busy tone multiple access (BTMA) [30] and receiver initiated BTMA (RI-BTMA) [31] that use out-of-band busy tone signal to prevent hidden nodes. Another popular collision avoidance mechanism is the multiple access with collision avoidance (MACA) [32] mechanism, which uses the request to send (RTS) and clear to send (CTS) messages to address the hidden terminal and exposed terminal problems. A modified version of MACA for wireless LAN, MACAW [33], enhances the performance of MACA by using additional data-sending (DS) and Ack control packets and a modified back-off mechanism. Floor acquisition multiple access (FAMA) [34] uses both carrier sensing and RTS-CTS to increase the channel throughput.

A popular example of CSMA/CA is the distributed foundation wireless MAC (DFWMAC) [35, 36], which is the basic access mechanism of IEEE 802.11 wireless LAN standards. DFWMAC takes advantage of the CSMA mechanism, combined with RTS-CTS-Data-Ack handshaking, a binary exponential backoff, different waiting intervals (inter-frame spaces), and the use of a network allocation vector (NAV) to keep track of the duration of the current transmission.

2.4 Wireless Home/Office Networking Standards

Many wireless home networking and personal area networking standards have emerged in recent years. Most of the devices communicating in the home will use one or more of these standards.

2.4.1 IEEE 802.11

The IEEE 802.11 standard [7] provides the PHY and MAC functionality for wireless LANs. It is comparable to IEEE 802.3 standard for Ethernet [37] wired LANs. Currently, three of IEEE 802.11 standards are most popular for wireless LAN applications and are being used throughout the world: IEEE 802.11b, IEEE 802.11a, and IEEE 802.11g. IEEE 802.11b is the most widely implemented wireless LAN technology today. It was originally designed to support infrared (IR), direct sequence spread spectrum (DSSS), and frequency hopping spread spectrum (FHSS) at 1 and 2 Mbps, but now supports up to 11 Mbps (average actual throughput of 4-5 Mbps) using DSSS. It operates at the 2.4 GHz ISM band and is subject to interference from other devices operating in this band such as cordless phones, microwave ovens, and bluetooth devices. IEEE 802.11a [8] operates in the 5 GHz frequency band and uses OFDM. It is capable of supporting up to 54 Mbps (actual average throughput of 27 Mbps). IEEE 802.11a is not compatible with IEEE 802.11b and has a shorter range of coverage. IEEE 802.11g also uses OFDM and is capable of supporting upto 54 Mbps (actual average throughput of 20-25 Mbps), but operates in the 2.4 GHz band. It is backward compatible with IEEE 802.11b and suffers from the same interferences in the 2.4 GHz band. For IEEE 802.11 standards, both ad hoc (distributed) and centralized topologies are supported. IEEE 802.11 was originally designed for transmission of data. An optional contention-free service has been added to support time-bounded services.

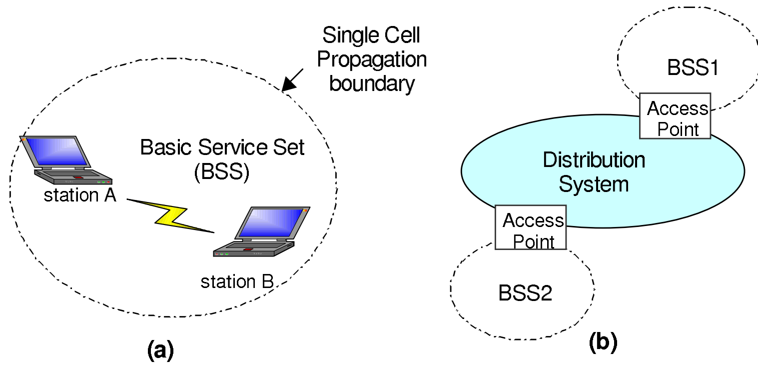


Figure 6: IEEE 802.11 Topologies: (a) IBSS, (b) ESS

2.4.1.1 Network Topology

The IEEE 802.11 standard supports the following two topologies:

- Independent Basic Service Set (IBSS): An IBSS (Figure 6a) is a basic service set (BSS) which follows an ad hoc network topology. The Mobile stations can talk to each other without the use of a master. However, if a cell contains many mobiles then the network planner has the option to setup a master for better link utilization.
- Extended Service Set (ESS): The ESS configuration (Figure 6b) consists of more than one BSS, which may be connected to another type of distribution service, such as Ethernet through an access point.

2.4.1.2 IEEE 802.11 MAC

The MAC functionality of 802.11 uses two methods to grant access to the channel (Figure 7):

- The Distributed Coordination Function (DCF) is used for contention services and is the primary access protocol for IEEE 802.11.
- The optional Point Coordination Function (PCF) is used for contention-free services. It uses a central controller, called the "point coordinator," (PC) and operates on top of DCF.

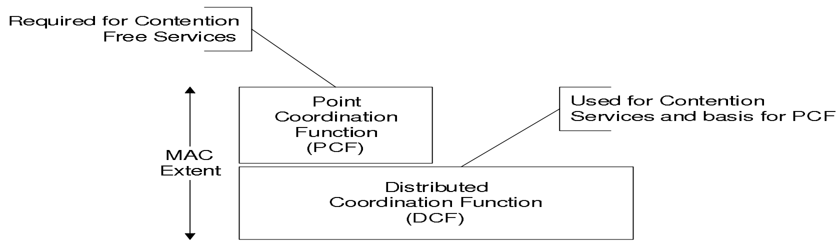
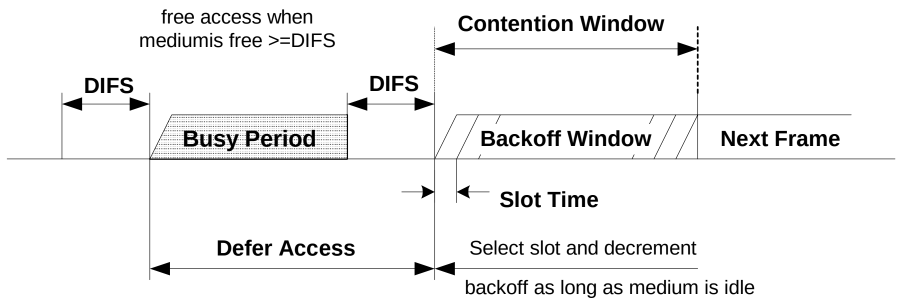


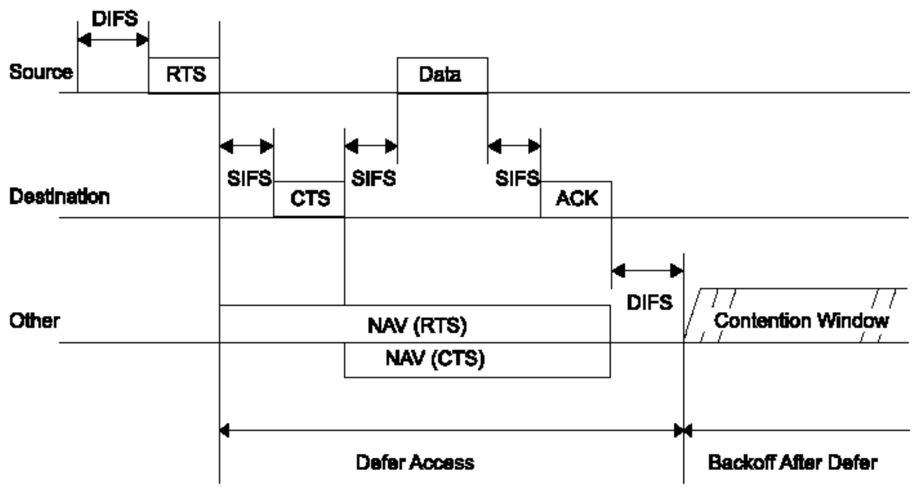
Figure 7: IEEE 802.11 Access Mechanisms

DCF Operation: The DCF operation is based on CSMA/CA, discussed in section 2.3.2. IEEE 802.11 also defines a handshaking mechanism similar to DFWMAC [35]: When a node wants to transmit, it sends a Request to Send (RTS) packet to the sender, indicating the expected duration of transmission. The receiver responds with a Clear to Send (CTS), giving the sender permission to send. All other stations hearing the RTS or CTS refrain from accessing the channel during the expected duration of transmission. Following a successful transmission, the receiver sends an Ack frame. This mechanism reduces the probability of collision, since the stations within the receiver's vicinity will hear the CTS and the hidden station problem is greatly eliminated. The CSMA/CA and RTS/CTS operations of the DCF scheme are shown in Figure 8. A more detailed explanation is provided in [5].

PCF Operation: The PCF provides an optional contention-free protocol in order to support time-bounded services. At the beginning of the contention-free period (CFP) the PC senses the medium. If the medium remains idle for a time interval of Point Inter Frame Spacing (PIFS), the PC sends a beacon containing the duration of transmission. All stations receiving the beacon defer from accessing the medium using DCF for this period. The PC polls the CF-pollable stations in its list one by one using the CF-poll frame. Each polled station responds with a CF-Ack (if it has no data to send) or Data+CF-Ack (if it has data to send). If the PC fails to receive an Ack for a transmitted data frame, it waits for a PIFS interval before proceeding to the next station in the list. An example of this operation is shown in Figure 9.



(a)CSMA/CA Mechanism



(b)RTS/CTS Mechanism

Figure 8: IEEE 802.11 DCF Operation

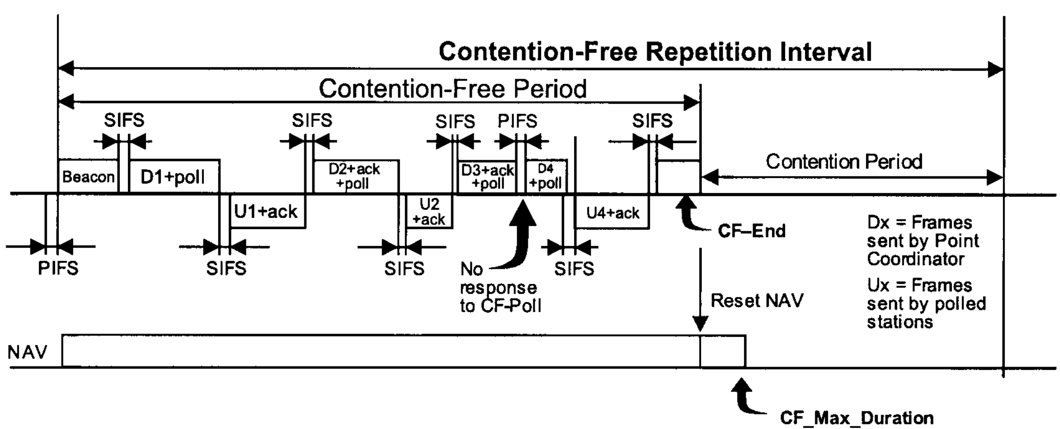


Figure 9: IEEE 802.11 PCF Operation: PC-to-Station transmission

2.4.2 Bluetooth

Bluetooth [38] is a wireless technology for short-range, low-power, low-cost radio connectivity between electronic devices such as desktop computers, electronic organizers, and cell-phones. It uses a 2-level Gaussian Frequency Shift Keying (GFSK) modulation. A single unit can support a maximum data rate of 721 kbps and a maximum of 3 voice channels (total 1 Mbps). Bluetooth supports both time-sensitive services such as voice, and asynchronous services such as data.

Bluetooth uses FHSS; a set of 79 hop carriers have been defined at a 1 MHz spacing, starting at 2.402GHz and finishing at 2.480GHz. In a few countries (i.e France) this frequency band range is (temporarily) reduced, and a 23-hop system is used [39]. Each Bluetooth device can be classified into one of three power classes:

- Power Class 1: is designed for long range (100m) devices, with a max output power of 20 dBm.
- Power Class 2: is for ordinary range devices (10m) devices, with a max output power of 4 dBm.
- Power Class 3: is for short range devices (10cm) devices, with a max output power of 0 dBm.

Each Bluetooth unit has its own pseudo-random hopping sequence, determined by its unique identity. The particular sequence is determined by the unit that controls the FH channel, referred to as the master. All other stations are slaves, and use the master's hopping sequence to synchronize with it [40, 41]. Time- division duplexing (TDD) is used, in which a unit alternately transmits and receives (Figure 10). This prevents cross talk between the transmitted and the received signals at the transceiver. Since transmission and reception occur at different times, they also occur at different frequencies.

2.4.2.1 Network Topology

Bluetooth uses the ad-hoc structure shown in Figure 11b, referred to as "scatternet." The scatternet topology consists of many independent ad-hoc networks coexisting in the same area, where each network (referred to as a piconet) can contain a maximum of eight stations [40].

2.4.2.2 Bluetooth MAC

The MAC mechanism in bluetooth is completely contention-free. The short dwell time in each frequency hop allows only a single packet transmission. A contention-based access would introduce too much overhead. Each station can become a master or a slave, with the role of the master/slave lasting only for the duration of the piconet. By definition, the unit that establishes the piconet becomes the master and will supervise medium access and traffic control. The time slots are alternatively used for master and slave transmissions. Polling is used for this purpose, where the master decides which slave can transmit next. If the master has data to send for a specific slave, the slave address is included in the message. After receiving the message, the slave is polled implicitly and can transmit in the next slot. If the master has no information to send, it polls the slave explicitly using a short poll packet [40].

Packet-Based Transmission: Bluetooth uses packet-based transmission. All packets contain an access code that includes the identity of the master and is used by the receiver to determine if the packet belongs to the piconet. As shown in Figure 12, the packets can occupy 1, 3, or 5 slots depending on the packet type. Only odd-number slots are used, in order to make sure that the transmit/receive timing is maintained. Multi-slot packets are sent on a single hop carrier so that there’s no frequency switch in the middle of a packet. The next packet uses the hop frequency specified by the master clock at that time [41].

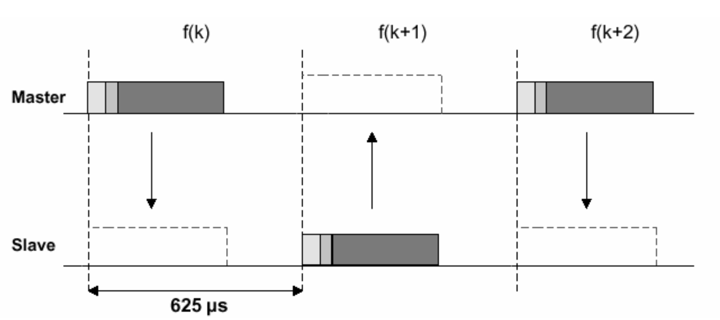


Figure 10: FHSS/TDD Mechanism in Bluetooth

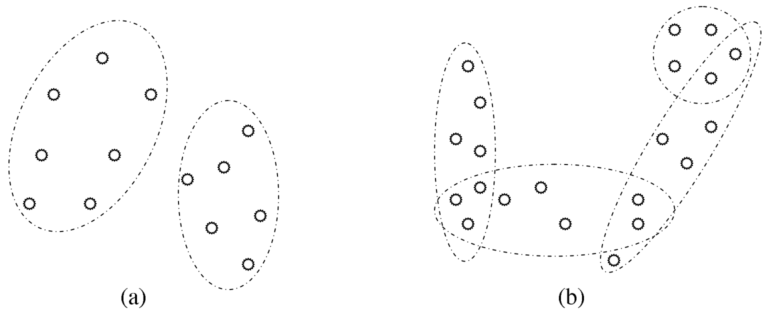


Figure 11: (a) Conventional Ad-hoc Systems, (b) Scatternet Topology

Bluetooth supports both synchronous services such as voice, and asynchronous services such as data. Synchronous traffic is supported by a circuit-switched point-to-point link (between the master and a slave), referred to as the Synchronous Connection-Oriented (SCO) link. The SCO link is established by reservation of duplex slots at regular time intervals. Asynchronous traffic is supported by the packet-switched Asynchronous Connectionless (ACL) link. The ACL link uses those remaining slots not used by the SCO link. Figure 13 shows an example of mixing SCO and ACL links on a single piconet channel [40, 41].

2.4.2.3 Power Management

In Bluetooth, special attention had been paid to efficient power management. The Bluetooth controller operates in two major states: *Standby* and *Connection*. Before connection, a unit is in *standby* mode. This is the default low-power state. In this state, only the native clock is running and there is no interaction with any other device; the unit sleeps most of the time, but wakes up at fixed intervals

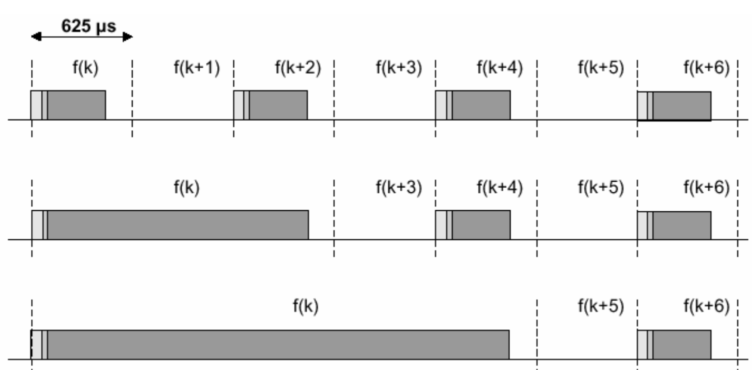


Figure 12: Frequency and Timing Properties of Bluetooth Packets

to scan the transmission for its access code. If the access code matches, it proceeds with the connection establishment process. A station requesting connection can either *page* the other unit if the address is already known or broadcast an *inquiry* message and ask the recipients for their address information. The *inquiry* procedure enables a device to discover which devices are in range, and determine the addresses and clocks for the devices. With the *paging* procedure, an actual connection can be established. The paging procedure typically follows the inquiry procedure. A unit that establishes a connection will carry out a page procedure and will automatically be the *master* of the connection. Once the connection is established, the devices are in the *connection* state. In the *connection* state, the master and slave can exchange packets.

A Bluetooth device in the *connection* state can be in any of the following states: *Active*, *Sniff*, *Hold* or *Park* mode. In the *Active* mode, the Bluetooth unit actively participates on the channel. The master schedules the transmission based on traffic demands to and from the different slaves. An active slave listens in the master-to-slave slots for packets. If the packet is not addressed to it, it goes back to sleep for the duration of packet. In the *Sniff* mode, the slave checks for master's transmissions at a reduced rate (regular intervals) and unless a packet is addressed to it, it sleeps the rest of the time. The sniff mode has a lower duty cycle than the active mode, but has the highest duty cycle (i.e., least power efficiency) among the other power saving modes. In the *Hold* mode, the slave goes into sleep for a *specified* duration, after which it becomes active. Data transfer restarts instantly when units transition out of hold mode. In the *Park* mode, the device sleeps for an

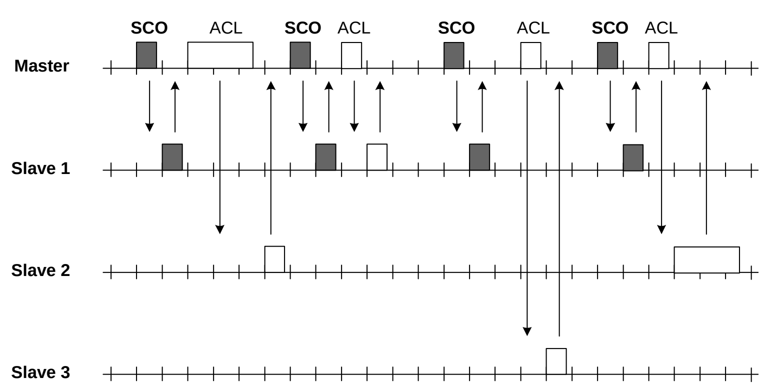


Figure 13: Mixing SCO and ACL Links on a Single Piconet Channel

unspecified duration; it is still synchronized to the piconet but does not participate in the traffic. The master has to specifically make the slave active at a future time. The park mode has the lowest duty cycle (highest power efficiency) of all 3 power saving modes. These states are shown in Figure 14. For more explanation the reader can refer to [2, 39–41].

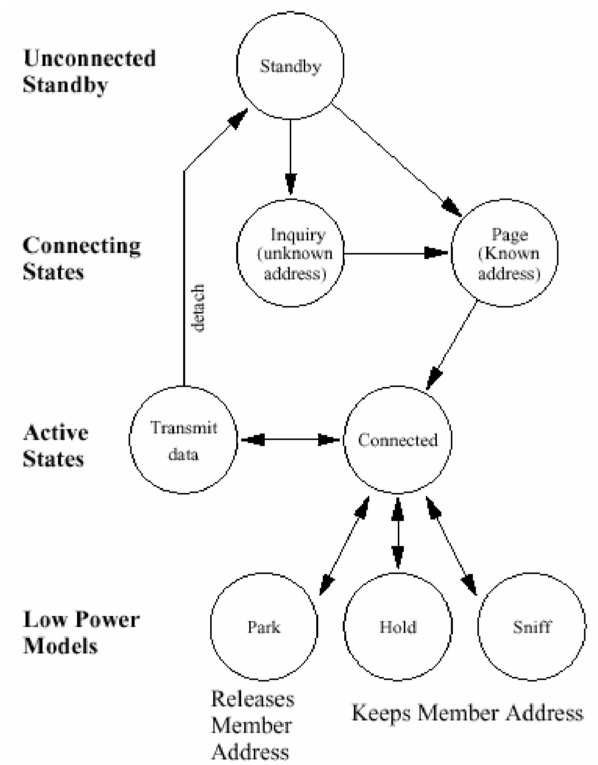


Figure 14: Bluetooth Connection States [2]

2.4.3 Comparison of Standards

Table 3 gives an overview of the standards discussed. IEEE 802.11 standards target professional and wireless LAN applications. Bluetooth has more relaxed specifications derived from 802.11, targeting cost-conscious consumers. They have relaxed the power requirements and transceiver complexity in order to reduce cost. Comparisons are controversial: each technology carries certain advantages/disadvantages and may prove useful for specific needs. Until a few years ago, IEEE 802.11 was mainly used in the office environments, but IEEE 802.11 has been spreading quickly. IEEE 802.11 not only offers higher data rates, but it also offers higher range (for the lower data rates) than Bluetooth. On the other hand, Bluetooth costs less and has been designed for voice and data, whereas 802.11a,b,g are optimized for data only. However, there have been ongoing efforts to improve on IEEE 802.11's time-bounded service performance (e.g., IEEE 802.11e) [42]. These technologies are somewhat complementary and will most likely co-exist to meet the demands of the future home.

Table 3: Comparison of Wireless Home Standards

	Bluetooth	**802.11b**	**802.11a**	**802.11g**
Data rates	1 Mbps	11 Mbps	54 Mbps	54 Mbps
Modulation	FHSS	DSSS, FHSS	OFDM	OFDM, DSSS, FHSS
Freq band	2.4 GHz	2.4 GHz	5 GHz	2.4 GHz
Typical Range	10 m	45 m	25 m	45m
Applications	Mobile Phones, Portable Terminals	Data	Data	Data
Real-Time QoS	Yes	No	No	No

2.5 UWB Technology

Recently, Ultra Wideband (UWB) technology has attracted a lot of interest in the research community and in industry. Unlike conventional radio systems, UWB operates across a wide range of frequency spectrum by transmitting a series of extremely narrow and low power pulses. As defined by the Federal Communications Commission (FCC) [6], UWB signals are those which have a fractional bandwidth greater than 0.20 measured at the -10 dB points, where fractional bandwidth is the ratio of the bandwidth occupied by the signal to the center frequency of the signal: $(F_H - F_L)/F_c$. The FCC [6] specifies that UWB can operate in the frequency range of 3.1-10.6 GHz with an indoor emission limit of -41 dBm/MHz. According to Shannon rule for channel capacity:

$$C = B \log_2 \left(1 + \frac{S}{N}\right) \tag{1}$$

where C is the maximum channel capacity in bits/s, B is the channel bandwidth in Hz, and S/N is the signal-to-noise ratio. Because the maximum channel capacity grows linearly with channel bandwidth, and only logarithmically with S/N, UWB has great room for achieving high capacities than systems that are more constrained by bandwidth [43, 44].

UWB offers many other great benefits: Because of its low power spread over large a bandwidth, UWB causes less interference than narrowband signals and has excellent multipath immunity and inherent security. UWB is capable of obtaining high-precision location information, due to the short duration of its pulses. This can be used in a number of ways in the physical layer, medium access (MAC), routing, etc. Finally, UWB systems could be made inexpensively and with low complexity, since the baseband pulse can be transmitted directly, reducing the hardware complexity.

2.5.1 UWB Modulation

In a baseband UWB system, each information-bearing symbol is represented by a number of pulses (N_{ps}). When using M-ary modulation, $\log_2 M$ bits are transmitted per symbol. Being real, baseband UWB transmissions don't have to use frequency modulation or phase modulation with $M > 2$ [45]. Symbol values are usually transmitted by modulating the position and/or the amplitude of the UWB pulse using one of the following techniques:

- Pulse Position Modulation (PPM) is the most popular (commonly studied/used) modulation in UWB. PPM encodes information by shifting the position of the transmitted pulse by specific amounts ($\delta_m, \quad m = 0, \ldots, M-1$), each representing one symbol value. Early development of UWB almost exclusively used PPM because negating the ultra-short UWB pulses were difficult to implement [45].

- On-Off keying (OOK) is another modulation scheme that does not require pulse negation. In OOK, the data is represented by presence or absence of a pulse (e.g., symbol ”1” is represented by transmitting a pulse, and symbol ”0” by transmitting nothing.)

- Pulse Amplitude Modulation (PAM) encodes the data by varying the amplitude in the pulse. Although M-ary PAM's energy-efficiency increases with increasing M, it is less attractive, since UWB communication systems are power-limited.

- Bipolar/Biphase modulation is a special case of PAM, where $M = 2$. In this modulation the binary data is represented by the polarity of the pulses (same as binary phase shift keying).

- A combination of these modulations could also be used, for example biphase modulation and orthogonal PPM can be combined to create a system using a biorthogonal signal set.

- These schemes can be further combined with Time Hopping (TH) or/and (amplitude) Spreading Codes to allow for multi-user access (MA). For example, time-hopping PPM (TH-PPM) is discussed in great detail in section 3.3.1. Direct Sequence (DS)-UWB can be used similar to traditional direct sequence spread spectrum (DSSS) mechanisms, except that instead of sinusoidal carriers, the UWB pulses are used. DS UWB has been studied and addressed in [46] and [47] among other publications.

2.5.2 UWB MAC

Given the superior capabilities of UWB and the rapid developments in this area, it is expected that UWB will quickly become a critical and integral part of the future home networks. Hence, an efficient and practical medium access control (MAC) mechanism is needed in order to share the wireless medium among the UWB stations. UWB systems could utilize a MAC similar to IEEE 802.11, based on Carrier Sense Multiple Access/Collision Avoidance (most likely for data), or use some form of a centralized or Time Division Multiple Access (TDMA) for time-bounded services.

2.5.3 UWB Standardization Efforts

The IEEE 802.15.3 [48] Task Group (TG3) for Wireless Personal Area Networks (WPANs) was formed to design a new standard for high-rate WPANs. Besides a high data rate, the IEEE 802.15.3 standard will provide for low power, low cost solutions addressing the needs of portable consumer digital imaging and multimedia applications.

An extension to this standard, IEEE 802.15.3a, was formed to support much higher rates (originally up to 480 Mbps, and even up to 1320 Mbps in some proposals) using UWB PHY for applications which involve imaging and multimedia. IEEE 802.15.3a started off with 23 UWB PHY proposals (from numerous companies) ranging from single carrier UWB to DS-CDMA UWB and MB-OFDM UWB. Over years of negotiations and going back and forth, the 23 proposals eventually merged into two proposals from two groups of companies, referred to as the WiMedia Alliance and the UWB Forum. However, these two groups could not resolve their differences and the IEEE 802.15.3a UWB standardisation attempt failed due to contrast between the two groups. On January 19, 2006 IEEE 802.15.3a task group (TG3a) members voted to withdraw the December 2002 project authorization request (PAR) that initiated the development of high data rate UWB standards [48]. There's no doubt that all the involved companies/groups will keep UWB technology alive, however, by offering a wide range of UWB products and technologies to the customers.

CHAPTER III

PHYSICAL LAYER ANALYSIS OF INTERFERENCE BETWEEN UWB AND IEEE 802.11A

As specified by the FCC, UWB can operate in the frequency range of 3.1-10.6 GHz with an indoor emission limit of -41 dBm/MHz. IEEE 802.11a wireless systems also operate in the 5 GHz U-NII band, which overlaps the allowed UWB band, and will most likely co-exist with UWB technology in the future home and office environments. This poses an important question on whether both technologies can coexist together, and how much interference they impose on each other.

We address the coexistence of UWB and IEEE 802.11a from two perspectives:

1. Investigate the interference from an IEEE 802.11a transmitter on an UWB receiver.

2. Investigate the interference from an UWB transmitter on an IEEE 802.11a receiver.

3.1 Interference Asymmetry between UWB and IEEE 802.11a

Using logical and analytical [49] tools it can be demonstrated that the interference between IEEE 802.11a and UWB is asymmetrical. To better understand this, consider Figure 15, which demonstrates the overlap of IEEE 802.11a and UWB systems in the frequency domain. It can be observed that all of the interference from IEEE 802.11a falls into the frequency band of the UWB system. In other words, all of the IEEE 802.11a signal, shaded with vertical stripes, may be picked up by the UWB receiver/antenna. However, only a small portion of the UWB signal falls into the frequency band of IEEE 802.11a system. This means that only the small portion of the UWB signal, shaded with a checkered pattern (perpendicular bars), will be picked up by the 802.11a receiver. The UWB signal in this case, appears as low power white noise with very little impact to the IEEE 802.11a receiver. In other words, although both systems interfere in one band of frequency, in that band, 802.11a is the dominant interferer.

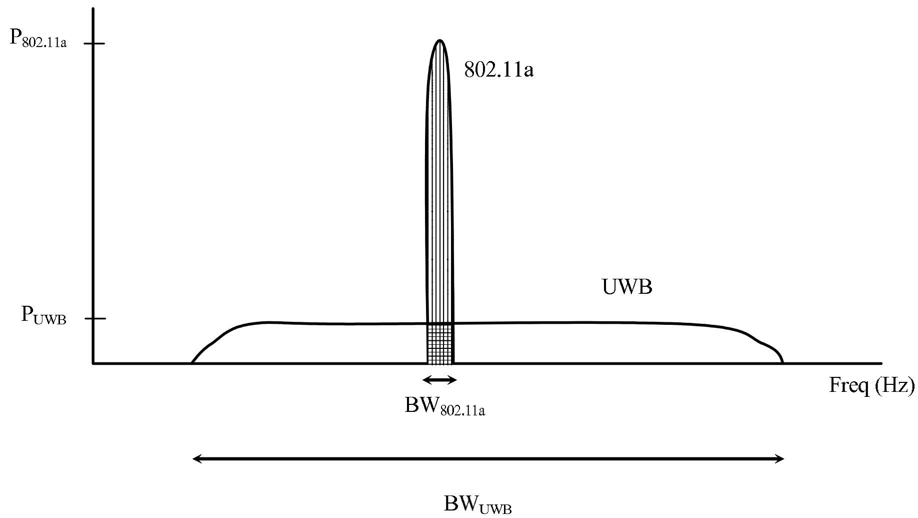


Figure 15: Interference Asymmetry between UWB and IEEE 802.11a

To demonstrate the relative interference from each source, consider the extreme case, when both UWB and 802.11a transceivers are located at the same location and transmit at their maximum-allowed power at the same time. Assume an UWB bandwidth of $BW_{UWB} = 7.5\ GHz$ and an IEEE 802.11a bandwidht of $BW_{802.11a} = 20\ MHz$. Using an UWB transmitted power of $P_{UWB} = 10^{-4.13} = 7.413e-5\ mW/MHz$, and either of the three 802.11a transmission powers ($P_{802.11a} = 2.5\ mW/MHz$ or 12.5 mW/MHz in the lower U-NIII or $P_{802.11a} = 50\ mW/MHz$ in the upper U-NIII bands), the signal to interference ratios at the UWB receiver (SIR_{UWB}) and at the IEEE 802.11a receiver ($SIR_{802.11a}$) can be calculated as follows:

$$SIR_{UWB} = \frac{P_{UWB}.\,BW_{UWB}}{P_{802.11a}.\,BW_{802.11a}} = \begin{cases} 0.011 \quad , & P_{802.11a} = 2.5mW/MHz \\ 0.0022 \quad , & P_{802.11a} = 12.5mW/MHz \\ 5.56E-4\ , & P_{802.11a} = 50mW/MHz \end{cases} \tag{2}$$

$$SIR_{802.11a} = \frac{P_{802.11a}.\,BW_{802.11a}}{P_{UWB}.\,BW_{802.11a}} = \begin{cases} 3.4E4\ , & P_{802.11a} = 2.5mW/MHz \\ 1.7E5\ , & P_{802.11a} = 12.5mW/MHz \\ 6.7E5\ , & P_{802.11a} = 50mW/MHz \end{cases} \tag{3}$$

Observe that $SIR_{UWB} \ll SIR_{802.11a}$. Therefore, in the case of total interference and total power reception, 802.11a performs extremely well, whereas UWB will be degraded significantly. The interference from an UWB system on an IEEE 802.11a system is minimal and in most situations, harmless. However, the interference from the same IEEE 802.11a on the UWB system is a lot more significant and critical. The main reason for this is that for both cases the interference is within the same band of frequency (20 MHz). Within that band, IEEE 802.11a is the dominant interferer. Moreover, most receivers, including the correlation receiver, are designed with white noise in mind. The IEEE 802.11a receiver is less affected by UWB noise, as UWB interference behaves similar to white noise over the receiver bandwidth. However, UWB receiver is affected more strongly, since the noise from IEEE 802.11a is similar to impulse noise and does not behave like white noise. It is because of this asymmetry that we focus mainly on the more critical issue of IEEE 802.11a interference in this thesis.

3.2 Interference of UWB on IEEE 802.11a

The transmitter and receiver block diagram for the 802.11a standard are shown in Figure 16. Assume a rectangular window function at the receiver, perfect frequency and timing synchronization, and a perfect channel estimation. Moreover, assume an ideal A/D convertor in the receiver with an infinite dynamic range, integrating all the energy in the received UWB signal.

Compared to the UWB bandwidth, the bandwidth of the 802.11a system is very small. Since the UWB signal energy is spread over a large frequency range, only a small portion of its total radiated power is within the spectrum of IEEE 802.11a receiver. As a result, the UWB power spectral density (PSD) will be basically constant (flat) over the bandwidth of the 802.11a signal that is admitted at the receiver filter, acting as low power white noise. Therefore, the UWB will essentially raise the noise floor of the received OFDM signal. If P_{UWB_R} represents the received power from the UWB signal, and BW_{OFDM} and BW_{UWB} represent the bandwidths of the OFDM and UWB signals, respectively, the interference power from the UWB signal will approximately be:

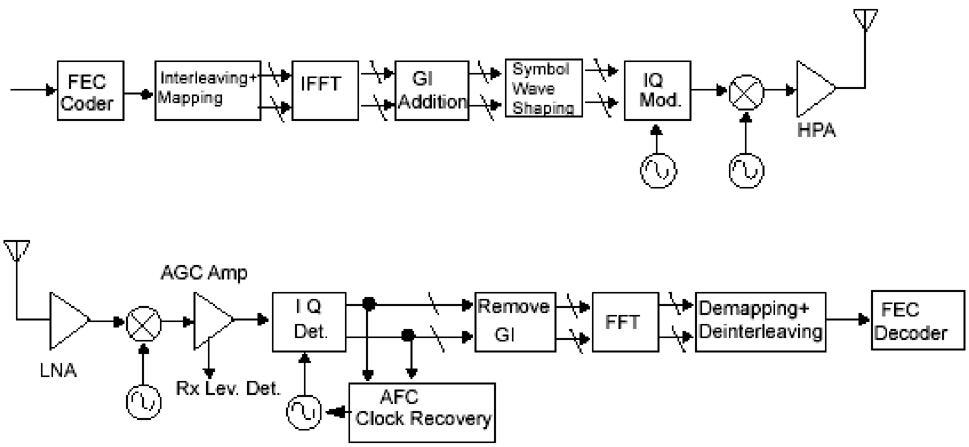


Figure 16: Transmitter and Receiver Block Diagram for 802.11a OFDM

$$P_{UWB_{int}} = \left(\frac{BW_{OFDM}}{BW_{UWB}}\right) P_{UWB\_R} \tag{4}$$

Given, that we are employing a 64-point FFT in our receiver, and the fact that the OFDM signal has 52 subcarriers, the SINR for each subcarrier can be estimated as:

$$SINR = \frac{P_{OFDM\_R}/52}{(\frac{BW_{OFDM}}{BW_{UWB}})(\frac{P_{UWB\_R}}{64}) + P_{N_0}} = \frac{1}{\frac{52}{64}(\frac{P_{UWB\_R}}{P_{OFDM\_R}}) + \frac{1}{SNR}} \tag{5}$$

where P_{OFDM_R} and P_{UWB_R} represent the received power from the OFDM and UWB signals, and BW_{OFDM} and BW_{UWB} represent the bandwidths of the OFDM and UWB signals, respectively.

The received power P_R (e.g., P_{OFDM_R} or P_{UWB_R}) is proportional to the corresponding transmitted power P_t (e.g., P_{OFDM_t} or P_{UWB_t}) by the relationship:

$$P_R(d) = \frac{P_t G_t G_r}{PL(d)}\ , \quad \text{or expressed in dB :} \quad P_R = P_t + G_t + G_r - PL(d) \tag{6}$$

where $PL(d)$ is the path loss, and G_t and G_r are the receiving and transmitting antenna gains.

The path loss $PL(d)$ (in dB) may be expressed as:

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + S \ ; \quad d \geqslant d_0 \tag{7}$$

where $PL(d_0)$ is the mean path loss in dB at close-in reference distance d_0, n is the path loss exponent, and d represents the distance between the transmitter and the receiver.

The reference distance, d_0, is chosen to be in the far-field of the transmitting antenna, at a distance at which the propagation can be considered to be close enough to the transmitter such that multipath and diffraction are negligible and the link is approximately that of free-space. The parameter S, known as *shadow fading*, is a zero-mean Gaussian random variable (in dB) that represents the error between the actual and the estimated path loss. The received signal power in the presence of shadowing is called the *local mean*, while the received signal power in the absence of shadowing is called the *area mean* [14]. Alternatively, a narrowband path loss model (8) has been used in many publications, where λ represets the wavelength corresponding to the center frequency of the signal. For free space propagation, a value of $n = 2$ is used.

$$PL(d) = \left(\frac{4\pi d}{\lambda}\right)^n \tag{8}$$

To provide a comparison between these different channel conditions/models, we plot the UWB power versus distance in Figure 17. We focus on the area mean, and use the $PL(d_0 = 1m)$ and n values determined empirically in [50] as $47dB$ and 1.7 for LOS paths; and $51dB$ and 3.5 for NLOS paths, respectively. Since the median path loss of a signal propagating through space is independent of its bandwidth [51], we use the same path loss model as in [50], developed at a center frequency of 5 GHz, for the IEEE 802.11a signal. Notice the fast signal degradation in the NLOS case, compared to the LOS case. Since the focus of our work is the study of interference effects, any of the above models can be used, as long as the comparisons made use the same model. Since the free space curve falls in between the other two (extreme) conditions/curves, we use the free space path loss model for our simulations throughout the thesis . Our techniques and equations can easily adapted for use with other channel models best describing the unique conditions of the channel in use.

We perform a simulation using the parameters of Table 4 in order to demonstrate the effects of UWB interference on IEEE 802.11a signal. We utilize a $7.5GHz$ bandwidth for UWB transmissions and a $20MHz$ bandwidth for IEEE 802.11a transmissions. The channel noise is assumed to

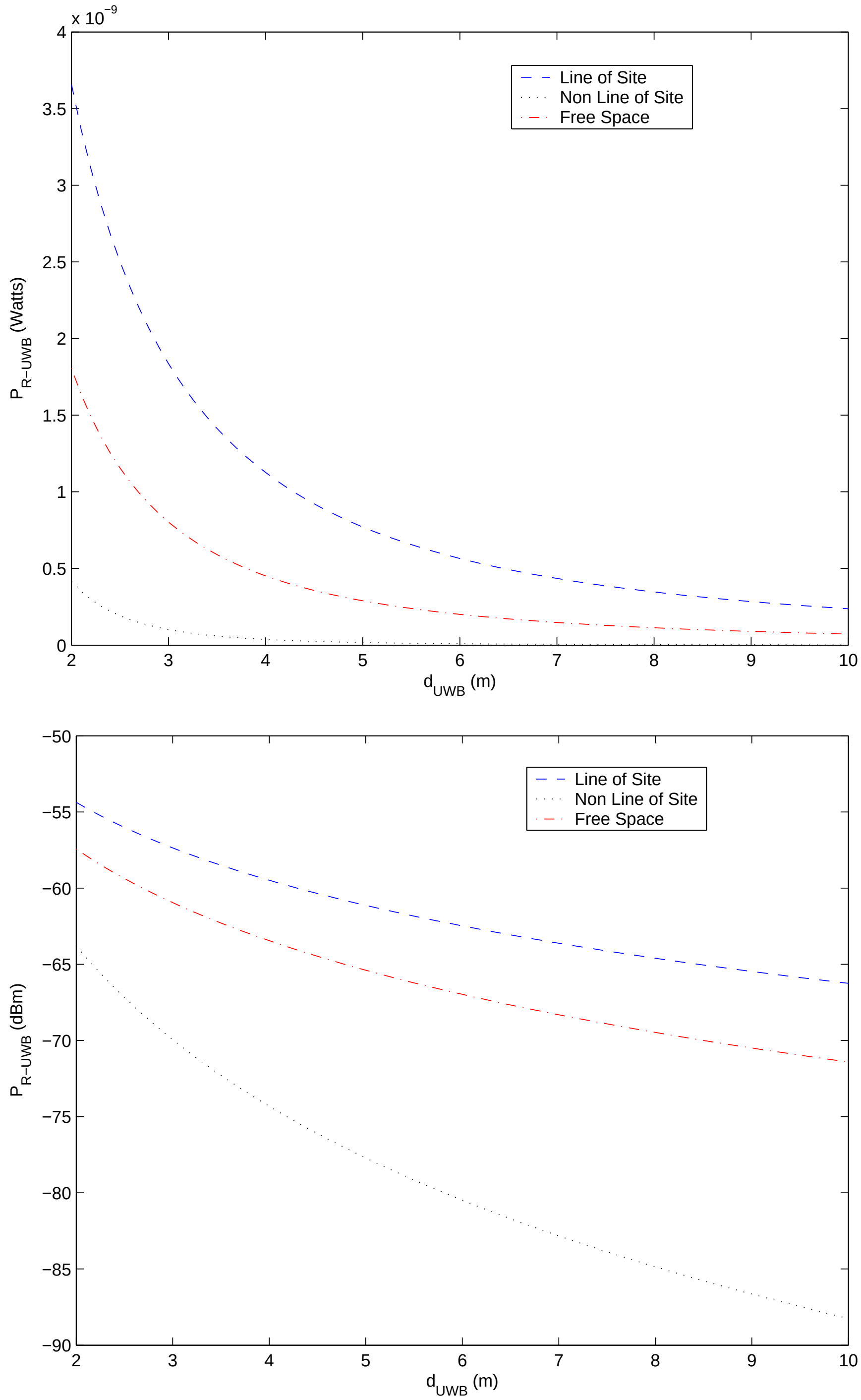


Figure 17: UWB Propagation for Different Channel Models/Conditions

Table 4: Simulation Parameters for UWB Interference on IEEE 802.11a

Parameter	Value
P_{UWB_t}	0.5957 mW
P_{OFDM_t}	40 mW
G_t	0 dB
G_r	0 dB
BW_{UWB}	7500 MHz
BW_{OFDM}	20 MHz
f_{c_UWB}	6.85 GHz
f_{c_OFDM}	5.22 GHz

be additive white Gaussian noise. Antenna gains are assumed to be $0dBi$, and a free space propagation model was used. The received signal to interference plus noise ratio (SINR) is shown in Figure 18 for different distances between the 802.11a receiver and 802.11a transmitter and UWB (interference) source. A range of 5-35m is used for d_{OFMD}, and a range of 2-10m is used for d_{UWB}. Please note the relatively small effect of UWB interference on the received 802.11a SINR, even at short distances of 2-3m. We chose the range of 2-10 m for d_{UWB}, since at higher distances the interference would remain negligible; had we plotted a larger range for d_{UWB}, the effects of interference at shorter distances (close to 2m) would not even be detectable in the graph.

The effect of the interference on the Bit Error rate (BER) for different $A_u : A_o$ ratios is shown in Figure 19. A_u and A_o are proportional to the square root of the received powers for UWB and OFDM, respectively. It can be observed that even when the UWB and 802.11a received signal strengths are equal (i.e., $A_u : A_o = 0dBr$), the effect of UWB interference on BER is very minimal, since most of the UWB interference power is spread over other frequencies and not picked up by the 802.11a receiver. Even when UWB signal strength is twice that of IEEE 802.11a signal (i.e., $A_u : A_o = 6dBr$), the change in BER is still not very high. Typical $A_u : A_o$ ratios are much lower than this, given the very low transmission power of the UWB systems compared to IEEE 802.11a systems.

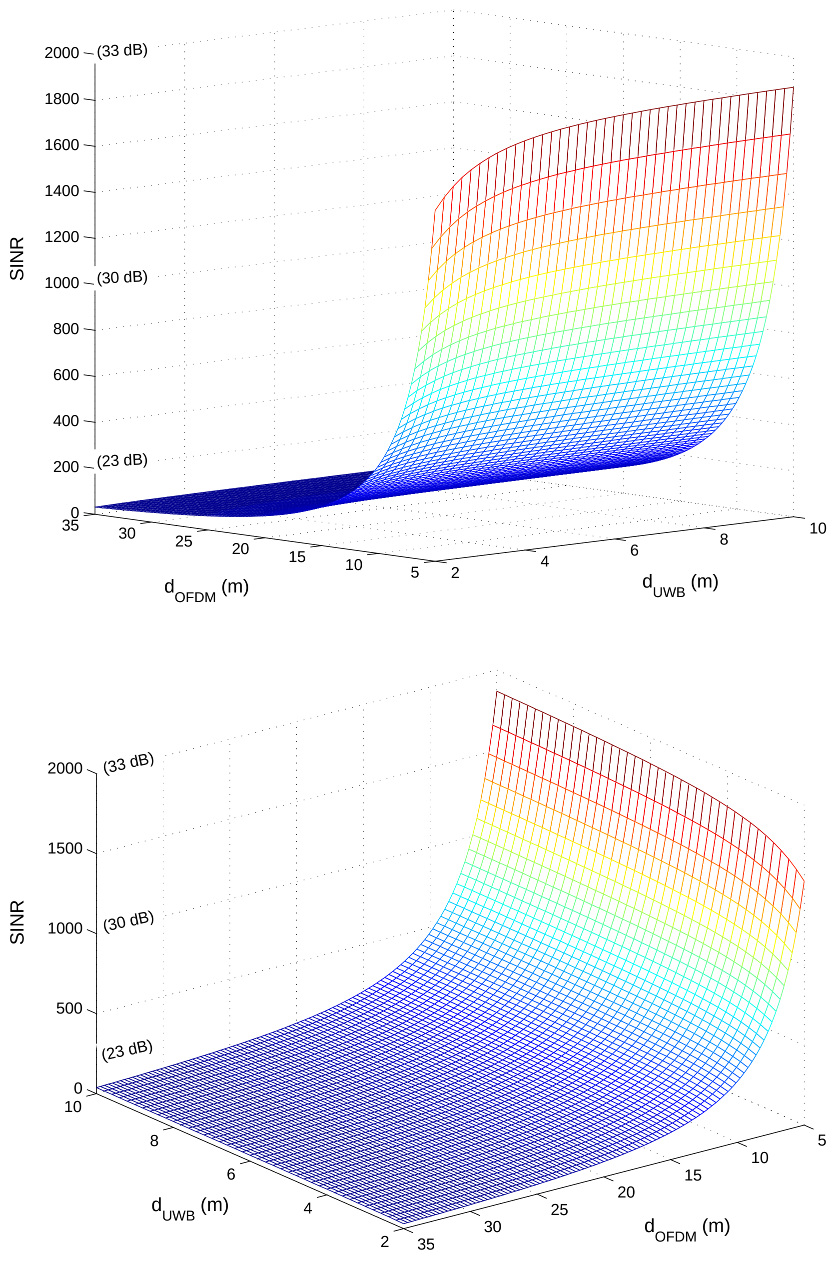


Figure 18: IEEE 802.11a SINR at different UWB and 802.11a source distances

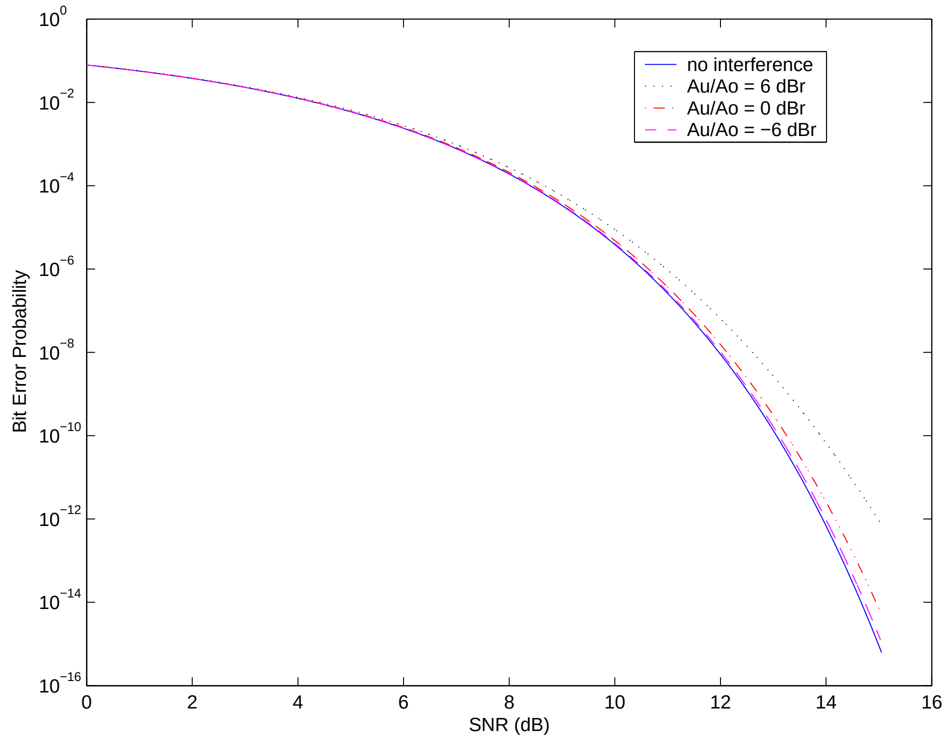


Figure 19: BER versus SNR in the presence of AWGN and UWB interference

In order to present a more typical (likely) scenario, and in an effort to show the BER floor for such a scenario, consider the case where the UWB and 802.11a transmitters are both equidistant, at 5m, away from the UWB receiver. In this case, the $A_u : A_o$ ratio is $-20ddBr$. The BER versus SNR curve for this case is plotted in Figure 20. Notice that at at even larger SNR values, corresponding to very small bit error rates, the UWB does not pose any tangible harm to the 802.11a system, and no BER floor can be found. In the next section we will compare this figure to one representing the effect of 802.11a interference on an UWB system for the same scenario, with some very interesting observations.

The dashed curves in figures 19 and 20 represent the upper limits for the probability of error due to interference and noise combined. The actual probability of error may fall in the region between the solid (no interference) curve and these upper bounds. Given $P(\alpha) = the\ probability\ of\ signal\ overlap$ and $P(\beta) = probability\ of\ no\ signal\ overlap$, the probability of error can be calculated as follows:

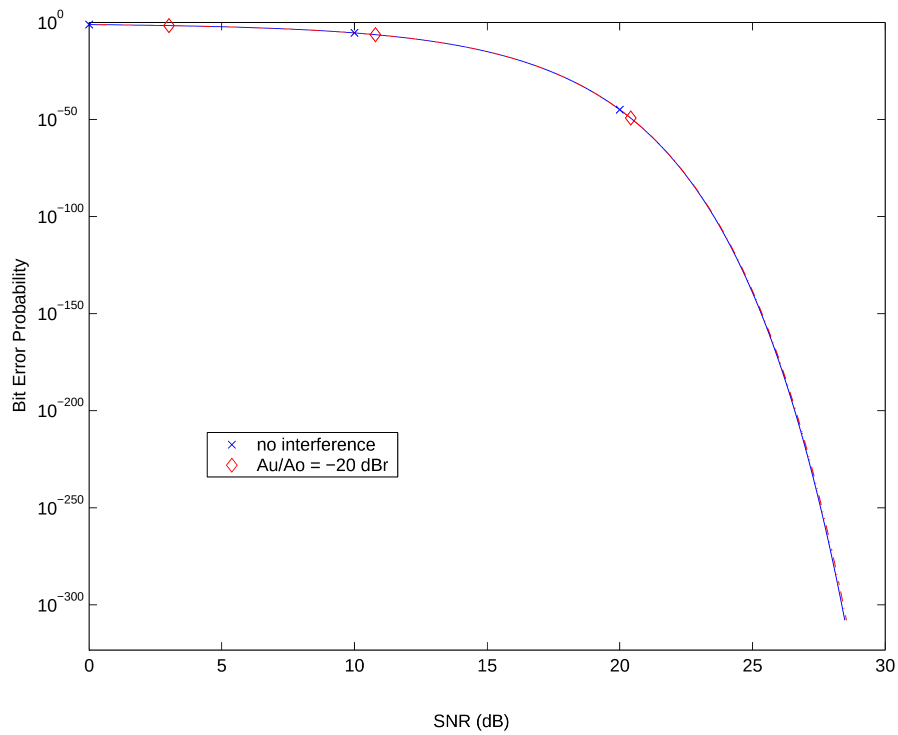


Figure 20: BER versus SNR in the presence of AWGN and UWB interference

$$P(error) = P(error|\alpha)P(\alpha) + P(error|\beta)P(\beta) \tag{9}$$

From our simulations, it can easily be inferred that the interference from the UWB source is negligible until the distance between the UWB source and the 802.11a receiver is much less than that between the 802.11a transmitter and receiver. Even then, the UWB interference poses minimal threat. This is expected, since the transmitted power of the UWB signal is so much smaller than that of the OFDM signal and is spread over a very wide spectrum; therefore, only a small portion of it will be received by the OFDM receiver. In most general cases, the UWB does not pose any serious threat to the performance of the IEEE 802.11a system. Because of this, most of research efforts focus on characterizing the interference from IEEE 802.11a systems and ways to mitigate it.

3.3 *Interference of IEEE 802.11a on UWB*

In this section, we evaluate the performance of an Ultra-Wideband receiver in the presence of IEEE 802.11a interference. A mathematical expression for the interference is presented, and a closed-form solution for the interference on an UWB system employing the second derivative Gaussian monocycle is derived. The interference is characterized in terms of the receiver's bit error rates and throughputs.

A number of ways can be used to represent the transmitted UWB signal. We adapt the following representation, to express a general form encompassing several different forms of UWB modulation and multi-user/multiple access (MA) schemes. User u's transmitted waveform can be expressed as:

$$s^{(u)}(t) = \sqrt{E_u} \sum_{p=0}^{\infty} a^{(u)}_{\lfloor p/N_{ps} \rfloor} \Lambda^{(u)}_p g\left(t - pT_f - c^{(u)}_p T_c - \delta b^{(u)}_{\lfloor p/N_{ps} \rfloor}\right) \tag{10}$$

where $g(t)$ represents the UWB monocycle, E_u is the u^{th} user's energy per pulse at the transmitter end, T_f is the time duration of a frame, N_{ps} represents the number of UWB pulses transmitted per symbol, δ is the PPM shift, $\Lambda^{(u)}_p$ and $c^{(u)}_p$ represent the (DS) amplitude code and time hopping sequence assigned to transmitter u during p^{th} frame, respectively, and T_c represents the duration of each time-hopping chip. The quantities with the superscript (u) indicate transmitter-dependent quantities. The notation $\lfloor p/N_{ps} \rfloor$ represents the integer part of p/N_{ps} to account for the oversampling in the system. The terms $a^{(u)}_{\lfloor p/N_{ps} \rfloor}$ and $b^{(u)}_{\lfloor p/N_{ps} \rfloor}$ are used to describe the M-ary information symbol $I^{(u)}_{\lfloor p/N_{ps} \rfloor} \in [0, M-1]$ transmitted, based on the modulation scheme used:

$$\begin{array}{lcll}
\text{M-ary PPM} & : & a^{(u)}_{\lfloor p/N_{ps} \rfloor} = 1 & , \quad b^{(u)}_{\lfloor p/N_{ps} \rfloor} = I^{(u)}_{\lfloor p/N_{ps} \rfloor} \\
\text{M-ary PAM} & : & a^{(u)}_{\lfloor p/N_{ps} \rfloor} = 2\, I^{(u)}_{\lfloor p/N_{ps} \rfloor} + 1 - M & , \quad b^{(u)}_{\lfloor p/N_{ps} \rfloor} = 0 \\
\text{M-ary OOK} & : & a^{(u)}_{\lfloor p/N_{ps} \rfloor} = I^{(u)}_{\lfloor p/N_{ps} \rfloor} & , \quad b^{(u)}_{\lfloor p/N_{ps} \rfloor} = 0
\end{array}$$

To allow for multi-user access to the UWB channel, different MA techniques can be used, e.g.:

- In TH-UWB, MA is achieved by changing the pulse *position* from frame to frame according to the time hopping code $c_p^{(u)}$.
- In DS-UWB, MA is achieved by changing the pulse *amplitude* from frame to frame, according to the amplitude (spreading) code, $\Lambda_p^{(u)}$.
- It is possible to combine the MA schemes, for example using both time hopping and amplitude code.
- It is also possible to use each MA scheme individually or to use none at all (i.e., $\Lambda_p^{(u)} = 1 \;\; \forall \; u, p$ if amplitude coding is not used, and $c_p^{(u)} = 0 \;\; \forall \; u, p$ if time hopping MA is not used).

3.3.1 IEEE 802.11a Interference on TH-PPM UWB Systems

Consider an Ultra Wideband (UWB) signal transmitted using time-hopping pulse position modulation (TH-PPM) [52]:

$$s^{(u)}(t) = \sum_p g\left(t - pT_f - c_p^{(u)}T_c - \delta b_{[p/N_{ps}]}^{(u)}\right) \tag{11}$$

For our analysis, we focus on only one station (transmitter 1) and we also assume perfect synchronization between the transmitter and the receiver. The received signal, $r(t)$, at the UWB receiver is composed of three parts: the desired UWB signal, additive white Gaussian noise $n_0(t)$, and the interference signal from the 802.11a system $n_I(t)$:

$$r(t) = A_u \, s^{(1)}(t) + n_0(t) + n_I(t) \tag{12}$$

where A_u represents the received amplitude of the UWB signal.

For an IEEE 802.11a system incorporating Orthogonal Frequency Division Multiplexing (OFDM), the transmitted signal can be represented as

$$s_{\text{OFDM}}(t) = w_T(t) Re\{\sum_{k=-N_{ST}/2}^{N_{ST}/2-1} c_k e^{j2\pi k \Delta F(t-T_G)} e^{j2\pi f_c t}\} \tag{13}$$

where N_{ST} represents the total number of subcarriers, c_k is the set of coefficients (data, pilot, etc.) transmitted, T_G is the guard time and ΔF represents the subcarrier frequency spacing. The function $w_T(t)$ is a time-windowing function that defines the boundaries of the subframe. For simplicity, we assume a rectangular $w_T(t)$ with unit amplitude.

For time hopping binary PPM, where $b^{(u)}_{[p/N_{ps}]} \in \{0, 1\}$ is a binary symbol stream, a bit duration correlation receiver is used with v_{bit} as the correlator template signal [52]:

$$v_{bit}(t) = g_{bit}(t) - g_{bit}(t - \delta), \tag{14}$$

where

$$g_{bit}(t) = \sum_{p=iN_{ps}}^{(i+1)N_{ps}-1} g(t - pT_f - c^{(1)}_p T_c), \tag{15}$$

The corresponding optimal decision rule is [52]:

$$\int_{T_{bit}} r(t)\, v_{bit}(t)\, \mathrm{d}t \begin{cases} > 0 \Leftrightarrow & \text{"0"}\ received \\ < 0 \Leftrightarrow & \text{"1"}\ received \end{cases} \tag{16}$$

We, then, calculate the OFDM interference at the receiver, $s_{int}(t)$, over one bit period of the UWB signal:

$$
\begin{aligned}
s_{int}(t) &= \int_{T_{bit}} A_2 \; s_{\text{OFDM}}(t) \; v_{bit}(t) \; \mathrm{d}t \\
&= A_o \sum_{p=0}^{N_{ps}-1} \left[\int_{pT_f}^{(p+1)T_f} Re\left\{ \sum_{k=-N_{ST}/2}^{N_{ST}/2-1} c_k e^{(j2\pi k\Delta F)(t-T_G)} \; e^{j2\pi f_c t} \right\} g\left(t - pT_f - c_p^{(1)} T_c\right) \; \mathrm{d}t \right. \\
&\left. - \int_{pT_f}^{(p+1)T_f} Re\left\{ \sum_{k=-N_{ST}/2}^{N_{ST}/2-1} c_k e^{(j2\pi k\Delta F)(t-T_G)} \; e^{j2\pi f_c t} \right\} g\left(t - pT_f - c_p^{(1)} T_c - \delta\right) \; \mathrm{d}t \right]
\end{aligned}
\tag{17}
$$

where A_o is the received amplitude of the OFDM interference signal.

Given that multiple(N_{ps}) repetitions of the UWB pulse are collected at the receiver for the duration of T_{bit}, some of the terms in equation (17) can be shifted to the origin and integrated over the short duration of the UWB pulse $g(t)$ for more feasible calculations. After some mathematical manipulations, we derive the final equation for the interference:

$$
\begin{aligned}
s_{int} = A_o \sum_{p=0}^{N_{ps}-1} \sum_{k=-N_{ST}/2}^{N_{ST}/2-1} Re\Big\{ c_k \; e^{-j2\pi k T_G \Delta F} \; e^{j2\pi (k\Delta F + f_c)(pT_f + c_p^{(1)} T_c + \xi)} \\
\cdot \left[1 - e^{j2\pi(k\Delta F + f_c)\delta}\right] \int_{-\xi}^{\xi} g_0(t) e^{j2\pi(k\Delta F + f_c)t} \mathrm{d}t \Big\}.
\end{aligned}
\tag{18}
$$

Here $g_0(t)$ is a pulse identical to $g(t)$, but unlike $g(t)$ which starts at time $t = 0$, $g_0(t)$ starts at $t = -\xi$, and has a duration of 2ξ. Since all or most of the UWB pulse's energy is contained within the $(-\xi, \xi)$ interval, the integration can be approximated closely by changing the integration limits from $(-\xi, \xi)$ to $(-\infty, \infty)$:

$$
\int_{-\xi}^{\xi} g_0(t) e^{j2\pi(k\Delta F + f_c)t} \mathrm{d}t \approx \int_{-\infty}^{\infty} g_0(t) e^{j2\pi(k\Delta F + f_c)t} \mathrm{d}t \tag{19}
$$

Depending on the properties of the transmitted pulse, we can then model or calculate the term inside the integral using a number of ways. For example in section 3.3.1.1 we use the properties of Gaussian pdf and in section 3.3.2.1 we use the Inverse Fourier Transform: If we define $x = 2\pi(k\Delta F + f_c)$ and rewrite g_0 as G_0 and t as w_t by simple change of notation, we can express the the integral term in (19) as an (Inverse) Fourier Transform:

$$\int_{-\infty}^{\infty} G_0(w_t) e^{jxw_t} \mathrm{d}w_t \;=\; 2\pi \mathscr{F}^{-1}\{G_0(w_t)\} \tag{20}$$

3.3.1.1 Interference for the second-derivative Gaussian Monocycle

An idealized received monocycle pulse commonly used in UWB literature is the second derivative Gaussian monocycle give by (21). We now try to find the interference for the case when $g_0(t)$ monocycle is expected at the UWB receiver:

$$g_0(t) = \left[1 - 4\pi\left(\frac{t}{\xi}\right)^2\right] e^{-2\pi\left(\frac{t}{\xi}\right)^2} \tag{21}$$

Substituting (21) into (18), and using the approximation of (19), the term inside the integral can be solved to obtain a closed-form solution. After extensive manipulation, the integral term can be written as:

$$\begin{aligned}&\int_{-\infty}^{\infty}\left[1 - 4\pi\left(\tfrac{t}{\xi}\right)^2\right] e^{-2\pi\left(\frac{t}{\xi}\right)^2} e^{j2\pi(k\Delta F + f_c)t}\mathrm{d}t \;=\\ &\qquad \sqrt{\frac{\xi^2}{2}}\int_{-\infty}^{\infty}\frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{(t-\mu_1)^2}{2\sigma^2}}\, e^{j\Omega t}\mathrm{d}t \;-\; \frac{4\pi}{\xi\sqrt{2}} e^{-\frac{(\Omega\xi)^2}{8\pi}}\int_{-\infty}^{\infty}\frac{t^2}{\sqrt{2\pi\sigma^2}} e^{-\frac{(t-\mu_2)^2}{2\sigma^2}}\mathrm{d}t\end{aligned} \tag{22}$$

where

$$\Omega = 2\pi(k\Delta F + f_c), \qquad \mu_1 = 0, \qquad \mu_2 = j(\frac{\Omega\xi^2}{4\pi}), \qquad \sigma^2 = \frac{\xi^2}{4\pi}.$$

Using the following properties of a Gaussian pdf,

$$\int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{(t-\mu)^2}{2\sigma^2}}\, e^{j\Omega t}\mathrm{d}t = \exp(j\Omega\mu - \frac{\sigma^2\Omega^2}{2}), \tag{23}$$

$$\int_{-\infty}^{\infty} \frac{t^2}{\sqrt{2\pi\sigma^2}} e^{-\frac{(t-\mu)^2}{2\sigma^2}}\mathrm{d}t = \sigma^2 + \mu^2, \tag{24}$$

we can now derive the closed form solution for the interference:

$$s_{int} \simeq \frac{\xi^3\pi}{\sqrt{2}} A_o \sum_{p=0}^{N_{ps}-1} \sum_{k=-N_{ST}/2}^{N_{ST}/2-1} Re\Big\{ c_k(f_c + k\Delta F)^2\, e^{j2\pi[(k\Delta F+f_c)(pT_f + c_p^{(1)}T_c + \xi) - k\Delta F T_G]} \cdot [1 - e^{j2\pi(k\Delta F + f_c)\delta}]\, e^{-\frac{\xi^2\pi}{2}(f_c + k\Delta F)^2} \Big\} \tag{25}$$

Equation (25) can also be obtained by using the technique presented in (20). It is important to notice that (25) calculates the interference for the case when both the UWB and 802.11a sources are transmitting at the same time. The actual (average) interference in the system, may be much less, depending on the network load, and is equal to the s_{int} multiplied by the probability of signal overlap.

3.3.2 IEEE 802.11a Interference on DS-PAM UWB Systems

Referring back to (10), the UWB signal transmitted using DS-PAM can be written as:

$$s^{(u)}(t) = \sum_p a^{(u)}_{\lfloor p/N_{ps}\rfloor} \Lambda_p^{(u)} g\,(t - pT_f) \tag{26}$$

Again, focus on only one station (transmitter 1) and assume perfect synchronization between the transmitter and the receiver. The interference signal is that of an OFDM (IEEE 802.11a) system, expressed by (13). For simplicity, assume a rectangular $w_T(t)$ with unit amplitude.

A correlation receiver (or equivalently a set of matched filters) can be used, consisting of a bank of M correlators, corresponding to the set of reference signals. For a direct sequence binary PAM

(DS-BPAM) modulation where $a^{(u)}_{\lfloor p/N_{ps} \rfloor} \in \{-1, 1\}$, we can define a bit duration correlator with v_{bit} as the template signal:

$$v_{bit}(t) = \sum_{p=iN_{ps}}^{(i+1)N_{ps}-1} \Lambda_p^{(u)} g(t - pT_f) \tag{27}$$

The corresponding optimal decision rule is:

$$\int_{T_{bit}} r(t)\ v_{bit}(t)\ \mathrm{d}t \begin{cases} > 0 \Leftrightarrow & \text{"1"}\ received \\ < 0 \Leftrightarrow & \text{"0"}\ received \end{cases} \tag{28}$$

We, then, calculate the OFDM interference at the receiver, $s_{int}(t)$, over 1-bit period of the UWB signal:

$$\begin{aligned} s_{int}(t) &= \int_{T_{bit}} A_o\ s_{\text{OFDM}}(t)\ v_{bit}(t)\ \mathrm{d}t \\ &= A_o \sum_{p=0}^{N_{ps}-1} \int_{pT_f}^{(p+1)T_f} Re\left\{ \sum_{k=-N_{ST}/2}^{N_{ST}/2-1} c_k e^{(j2\pi k\Delta F)(t-T_G)}\ e^{j2\pi f_c t} \right\} \Lambda_p^{(1)} g\left(t - pT_f\right)\ \mathrm{d}t \end{aligned} \tag{29}$$

Given that multiple(N_{ps}) repetitions of the UWB pulse are collected at the receiver for the duration of T_{bit}, some of the terms in equation (29) can be shifted to the origin and integrated over the short duration of the UWB pulse $g(t)$ for more feasible calculations. After some mathematical manipulations, we derive the final equation for the interference:

$$\begin{aligned} s_{int} = A_o \sum_{p=0}^{N_{ps}-1} \sum_{k=-N_{ST}/2}^{N_{ST}/2-1} \Lambda_p^{(1)} Re\Big\{ c_k\ e^{-j2\pi k T_G \Delta F}\ e^{j2\pi(k\Delta F + f_c)(pT_f+\xi)} \\ \cdot \int_{-\xi}^{\xi} g_0(t) e^{j2\pi(k\Delta F + f_c)t} \mathrm{d}t \Big\} \end{aligned} \tag{30}$$

where $g_0(t)$ is a shifted copy of $g(t)$ that is centered at the origin; $g_0(t)$ starts at $t = -\xi$, and has a duration of 2ξ. Following the same steps and substitutions as (19) and (20), the integral term can be approximated by an (inverse) Fourier Transform:

$$\int_{-\xi}^{\xi} g_0(t) e^{j2\pi(k\Delta F + f_c)t} \mathrm{d}t \approx \int_{-\infty}^{\infty} G_0(w_t) e^{jxw_t} \mathrm{d}w_t \;=\; 2\pi \mathscr{F}^{-1}\{G_0(w_t)\} \tag{31}$$

3.3.2.1 Interference for the second-derivative Gaussian Monocycle

We now find the interference for the UWB monocycle pulse presented in (21). We have already derived the closed form expression for the integral term in section 3.3.1.1 using the first and second moment generating functions of a Gaussian pdf. In here, we solve the equation using the inverse Fourier transform substitution of (31).

Let's rewrite $g_0(t)$ as $G_0(w_t)$ by simple change of notation:

$$G_0(w_t) = \left[1 - 4\pi \left(\frac{w_t}{\xi}\right)^2\right] e^{-2\pi\left(\frac{w_t}{\xi}\right)^2} \tag{32}$$

Calculating the IFT, we obtain:

$$\mathscr{F}^{-1}\{G_0(w_t)\} = \frac{x^2 \xi^3}{8\sqrt{2}\pi^2} e^{-\frac{x^2 \xi^3}{8\pi}} \tag{33}$$

Multiplying by 2π and substituting $x = 2\pi(f_c + k\Delta F)$, we get:

$$\int_{-\infty}^{\infty} g_0(t)\; e^{j2\pi(k\Delta F + f_c)t}\; \mathrm{d}t \;=\; \frac{\xi^3 \pi}{\sqrt{2}}\; (f_c + k\Delta F)^2\; e^{-\frac{\xi^2 \pi}{2}(f_c + k\Delta F)^2} \tag{34}$$

The closed-form expression for the interference can now be obtained;

$$s_{int} \simeq \frac{\xi^3 \pi}{\sqrt{2}} A_o \sum_{p=0}^{N_{ps}-1} \sum_{k=-N_{ST}/2}^{N_{ST}/2-1} \Lambda_p^{(1)} (f_c + k\Delta F)^2 e^{-\frac{\xi^2 \pi}{2}(f_c + k\Delta F)^2} \cdot Re\Big\{ c_k\; e^{j2\pi[(k\Delta F + f_c)(pT_f + \xi) - k\Delta F T_G]} \Big\} \tag{35}$$

3.3.3 IEEE 802.11a Interference on TH-BPSK UWB Systems

For a time-hopping binary Phase Shift Keying (TH-BPSK) UWB correlation receiver, using the same decision rule as (28), the template signal, $v_{bit}(t)$, can be expressed as:

$$v_{bit}(t) = \sum_{p=iN_{ps}}^{(i+1)N_{ps}-1} g(t - pT_f - c_p^{(1)}T_c) \tag{36}$$

Following the same approach as in sections 3.3.1 and 3.3.2, the IEEE 802.11a interference received by this receiver is derived:

$$\begin{aligned} s_{int} = A_o \sum_{p=0}^{N_{ps}-1} \sum_{k=-N_{ST}/2}^{N_{ST}/2-1} Re\Big\{ c_k \, e^{-j2\pi kT_G\Delta F} \, e^{j2\pi(k\Delta F+f_c)(pT_f+c_p^{(1)}T_c+\xi)} \\ \cdot \int_{-\xi}^{\xi} g_0(t) e^{j2\pi(k\Delta F+f_c)t} \mathrm{d}t \Big\} \end{aligned} \tag{37}$$

If the UWB monocycle of (21) is used for $g_0(t)$, then using the results in section 3.3.2.1, we derive the closed-form expression for the interference:

$$\begin{aligned} s_{int} \simeq \frac{\xi^3\pi}{\sqrt{2}} A_o \sum_{p=0}^{N_{ps}-1} \sum_{k=-N_{ST}/2}^{N_{ST}/2-1} (f_c + k\Delta F)^2 e^{-\frac{\xi^2\pi}{2}(f_c+k\Delta F)^2} \\ \cdot Re\Big\{ c_k \, e^{j2\pi[(k\Delta F+f_c)(pT_f+c_p^{(1)}T_c+\xi)-kT_G\Delta F]} \Big\} \end{aligned} \tag{38}$$

Since the same basic approach as in previous sections is used, we have skipped the derivation steps in this section, providing only the final results.

3.3.4 Performance Evaluation

The interference, s_{int}, was calculated for 10^6 trials of UWB symbol transmissions using equations (25) and (35), the parameters of Table 5, and randomly generated OFDM symbols. Interference samples from one UWB pulse to the next were treated as independent, due to the fact that the UWB pulse repetition frequency of our system is less than the bandwidth of the OFDM signal. Additive white Gaussian channel (thermal) noise was assumed. The SNR and SINR values were calculated using the procedure outlined in [52].

Table 5: Simulation Parameters for IEEE 802.11a impact on UWB receiver

Parameter	Value
ξ	0.13×10^{-9}
δ	0.1×10^{-9}
T_f	80×10^{-9}
N_s	$4, 8$
f_c	5.22×10^{9}
N_{ST}	52
T_G	0.8×10^{-6}
ΔF	0.3125×10^{6}

For the case of TH-PPM UWB, a value of δ was selected that optimizes the performance of the correlation receiver. The monocycle pulse, $g(t)$, and the corresponding template signal, $v(t) = g(t) - g(t - \delta)$, is shown in Figure 21. We plot the histogram of s_{int} in Figure 22. The OFDM interference acts approximately as a zero-mean Gaussian noise [53, 54]. An alternative approach would be to model the IEEE 802.11a signal as a bandlimited additive white gaussian noise. However, this approach may need additional assumptions, for instance for the spectrum to be flat and to ignore the sidelobes of the spectrum. In our calculations, we addressed the interference as observed by the specific (e.g., time hopping PPM) correlation receiver, which depends on the pulse shape of the UWB signal, and is not necessarily time-invariant.

The effect of IEEE 802.11a interference on the Bit Error Probability for TH-PPM UWB is shown in Figure 23 for different A_o:A_u ratios. A_o and A_u are proportional to the square root of the received powers for OFDM and UWB, respectively. The solid line shows the BER without the presence of any interference (A_o:$A_u = -\infty\ dBr$). The dashed curves represent the upper limits for the BER when both noise and interference are present. Please note the significant increase in the bit error rate as A_o:A_u is increased. For example, when A_o:$A_u = 0\ dBr$, when the received OFDM

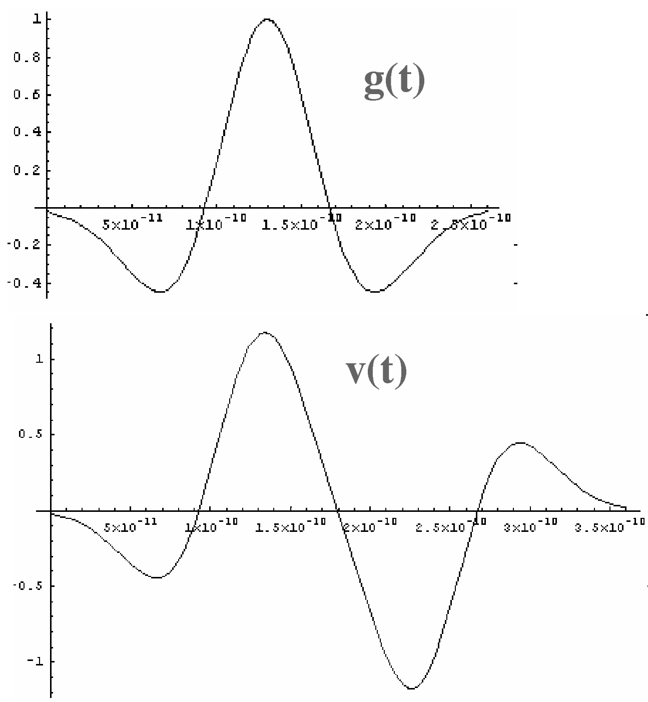


Figure 21: $g(t)$ and $v(t)$ used in our simulation

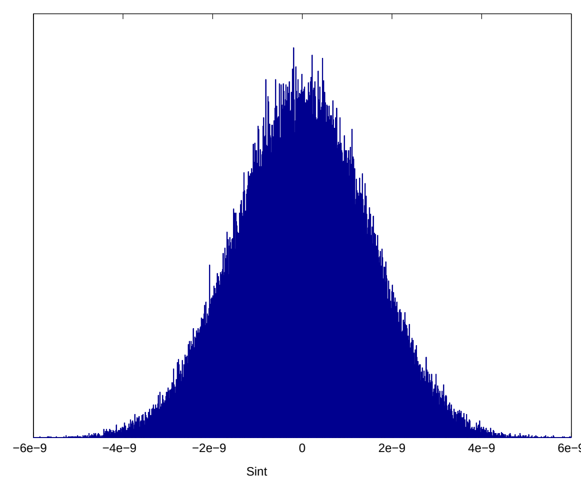


Figure 22: The Distribution of s_{int} interference

and UWB amplitudes are equal, the BER at SNR=14 has increased from $\approx 10^{-6}$ to $\approx 10^{-3}$. This scenario corresponds, in free space propagation, to an UWB transmitter-receiver separation of 7m and and an 802.11a interference source 72m away (or a $d_u : d_o$ ratio of ≈ 0.1).

In order to present a fair comparison (or a more typical scenario), consider the case where both

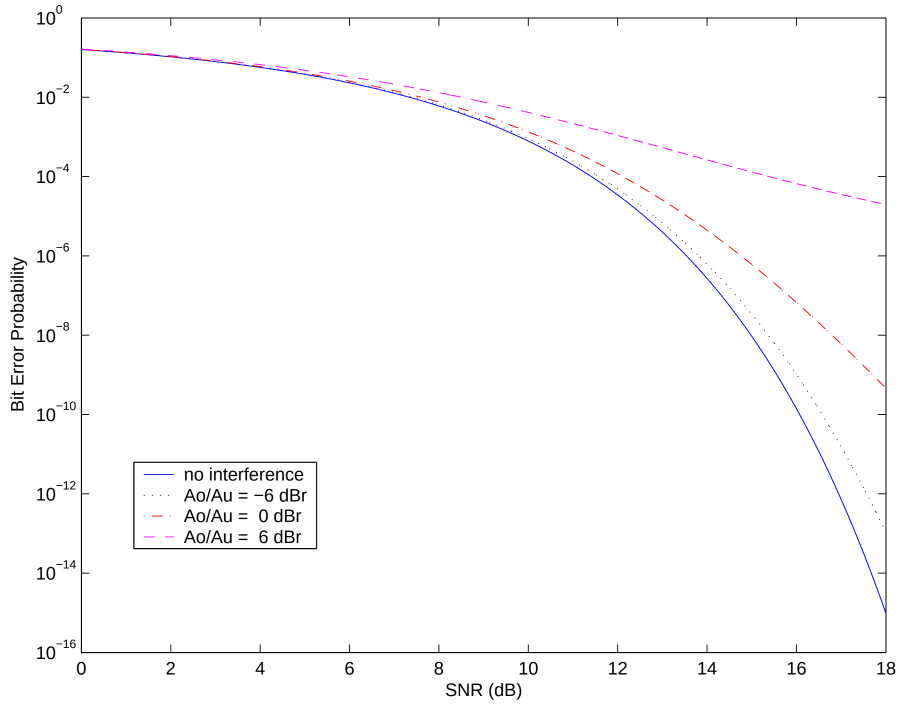


Figure 23: BER versus SNR for TH-PPM UWB in the presence of AWGN and 802.11a interference

UWB and 802.11a transmitters are equidistant, say 5m, away from the UWB receiver. The BER versus SNR curve for this scenario ($A-u : A_o = -20dBr$) is presented in Figure 24. Notice that even for low SNR (high BER) values, we've already reached the BER floor. In fact, the BER is constantly above 0.1, an unacceptable value for practically any wireless application. Compare this to Figure 20 to realize the true asymmetric nature of the interference the two systems impose on each other.

Using the very same procedure and applying the correlation template of (36) and the final equation (38), we can show the effect of 802.11a interference on TH-BPSK UWB in Figure 25. In general, TH-BPSK may outperform the TH-BPPM slightly and show better immunity to interference. However, the impact of the interference is still very significant, as shown in the figure. Again, we notice that for the typical scenario where $A-u : A_o = -20dBr$, the 802.11a interference practically makes the UWB system non-operational. In the rest of the chapter, we focus on TH-PPM simulations, since all other baseband modulations studied are impacted in a similar manner by 802.11a interference.

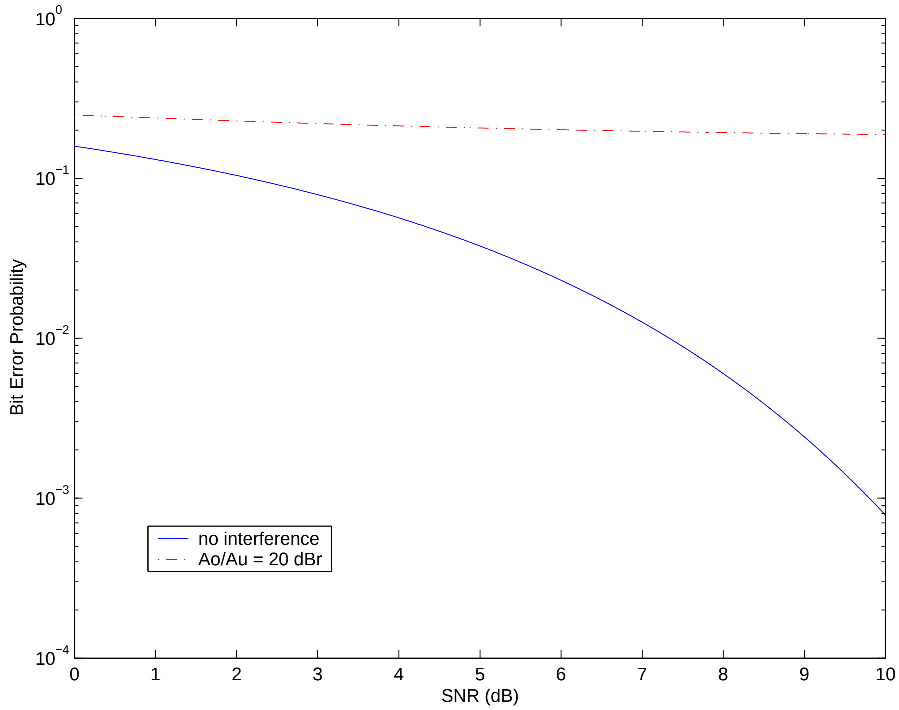


Figure 24: BER versus SNR for TH-PPM UWB in the presence of AWGN and 802.11a interference

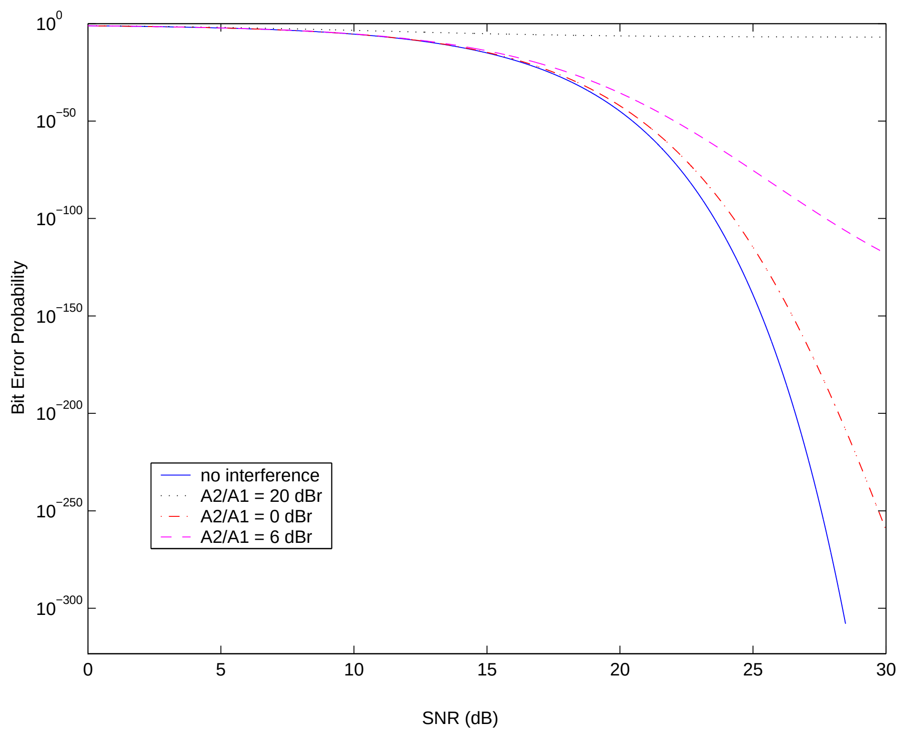


Figure 25: BER versus SNR for TH-BPSK UWB in the presence of AWGN and 802.11a interference

The significance of 802.11a interference becomes more clear when we compare the BER variations of Figure 23 with those of figure 19. Given the 802.11a PSD of 2.5mW/MHz, which is much larger than that of UWB (-41 dBm/MHz), typically (in most locations) we expect much higher $A_o : A_u$ values than $A_u : A_o$ values. The actual probability of error may fall in the region between the solid (no interference) curve and the dashed curves representing the upper bounds. Given $P(\alpha) = probability\ of\ signal\ overlap$ and $P(\beta) = probability\ of\ no\ signal\ overlap$, the probability of error can be calculated as:

$$P(error) = P(error|\alpha)P(\alpha) + P(error|\beta)P(\beta) \tag{39}$$

To get a better understanding of the UWB receiver performance at different distances from the UWB source and from the 802.11a (interference) source, we proceed with SINR and throughput analyses at different distances next. For these analyses, we utilize the whole 7.5 GHz bandwidth and assume that the spectrum is flat over the 3.1-10.6 GHz band. The transmit power spectral density is limited to -41 dBm/MHz. Antenna gains are assumed to be 0 dBi. A noise figure of 6 dB and an implementation margin of 2 dB are assumed. A target BER of 10^{-3} uncoded is used, and the channel noise is additive white Gaussian noise.

A comparison between the LOS, NLOS, and free space propagations models of section 3.2 is provided in Figure 26. We use the same $PL(d0)$ and n values as described in [50] and in section 3.2. The SNR of the received UWB signal at different distances from the source is shown. UWB signals degrade rather quickly, especially in NLOS conditions. Since the free space curve falls in between the other two extreme conditions/curves, it serves as a good representative model that we use for the rest of our simulations. Our techniques and equations can easily be adapted for use with other channel models best describing the unique conditions of the channel in use.

To get a realistic understanding of the performance of the UWB receiver at different distances from the UWB source and the 802.11a (interference) source, we simulate the SINR curve in Figure 27. A range of 5-50m is used for d_{OFMD}, and a range of 2-10m is used for d_{UWB}. Please notice how the SINR changes from over 14 to under 4, when the OFDM source moves close (from 50m to 5m) to the UWB receiver. Given an UWB SNR of ≈ 15 at $d_{UWB} = 2m$ in the absence of 802.11a interference (refer to Figure 26), this translates to a 73% drop in SNR as a result of an 802.11a source $5m$ away. In fact the effects of the 802.11a separation are more pronounced in this figure than the effects of the UWB separation. Compare this to Figure 18 where the effects of UWB interference are rather negligible in comparison.

The maximum achievable bit rate is calculated for our system, using the received UWB Power, $P_R(d)$ [55]:

$$R_{b,max} = \frac{P_R(d)}{E_b} = \frac{1}{E_b}\frac{P_t G_t G_r}{PL(d)} \tag{40}$$

where E_b is the effective received energy per bit.

The maximum achievable throughput versus d_{UWB} for different A_o:A_u ratios is shown in Figure 28. It can be observed that the interference can significantly reduce the achievable throughput. Please note that for each curve that is plotted here, the value of A_o:A_u remains constant. In other words, the amplitude of the received OFDM signal is changing as the amplitude of the received UWB signal is varied.

In order to better understand the effect of the interference, we plot the maximum achievable throughput versus the A_o:A_u ratio for four fixed d_{UWB}'s in Figure 29. As can be seen in the plot, the throughput decreases very quickly as A_o:A_u increases; at A_o:A_u ratio of 3 ($9.5\ dBr$) the throughput is at extremely low levels compared to the throughput at an A_o:A_u ratio of 0 ($-\infty\ dBr$), when there is no interference present. Since the d_{UWB} is kept constant for each curve, the increase in A_o:A_u can be interpreted an increase in the OFDM signal at the receiver, e.g., OFDM source moving closer to the UWB receiver.

Bear in mind that Figures 28 and 29 show the cases corresponding to the upper limits of BER (lower limits of throughput), when there is a complete overlap between the UWB and the 802.11a signals. Therefore, the impact of the interference may be less in a system where the probability of OFDM and UWB signal overlap is less.

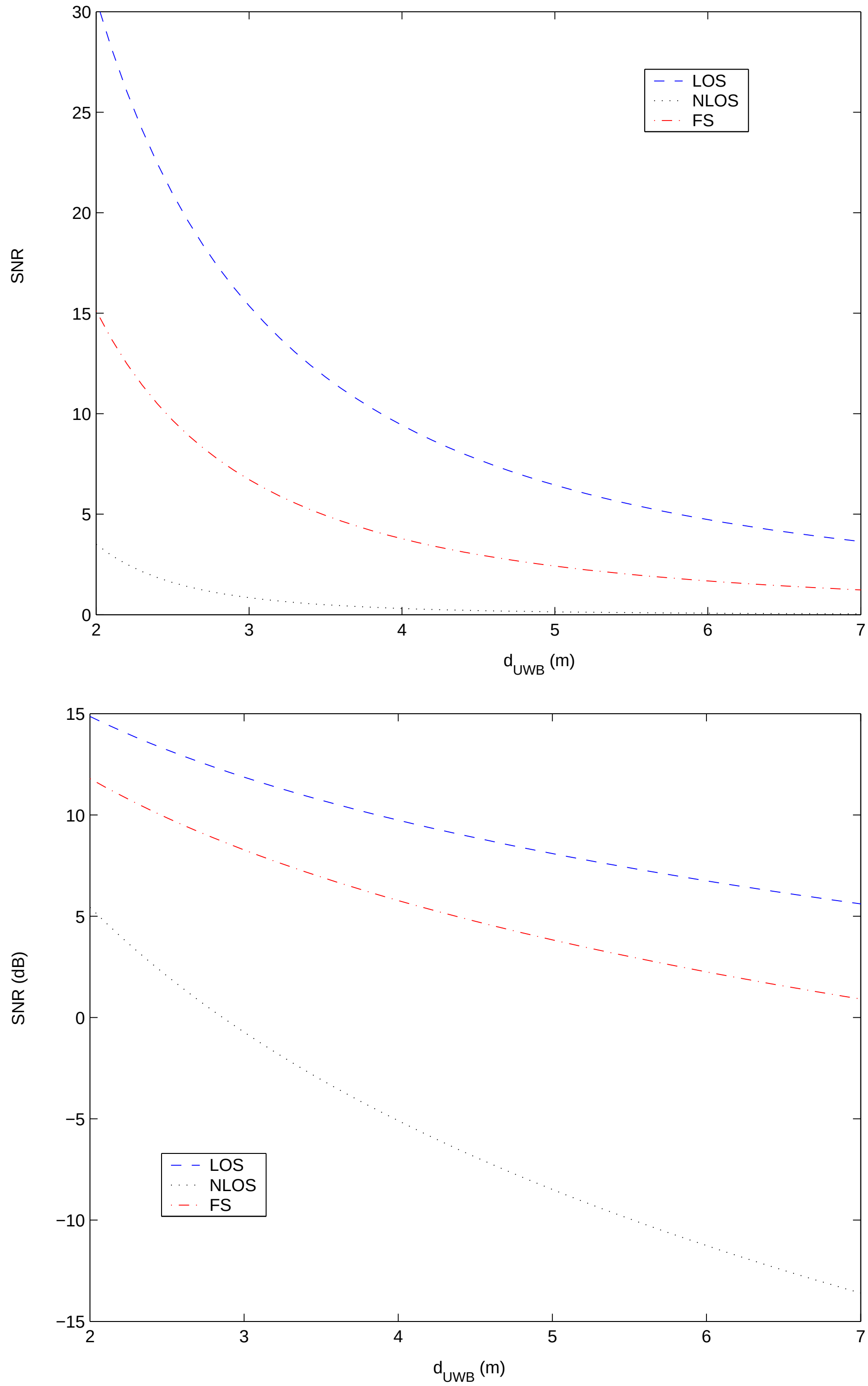


Figure 26: UWB SNR for Different Channel Models/Conditions

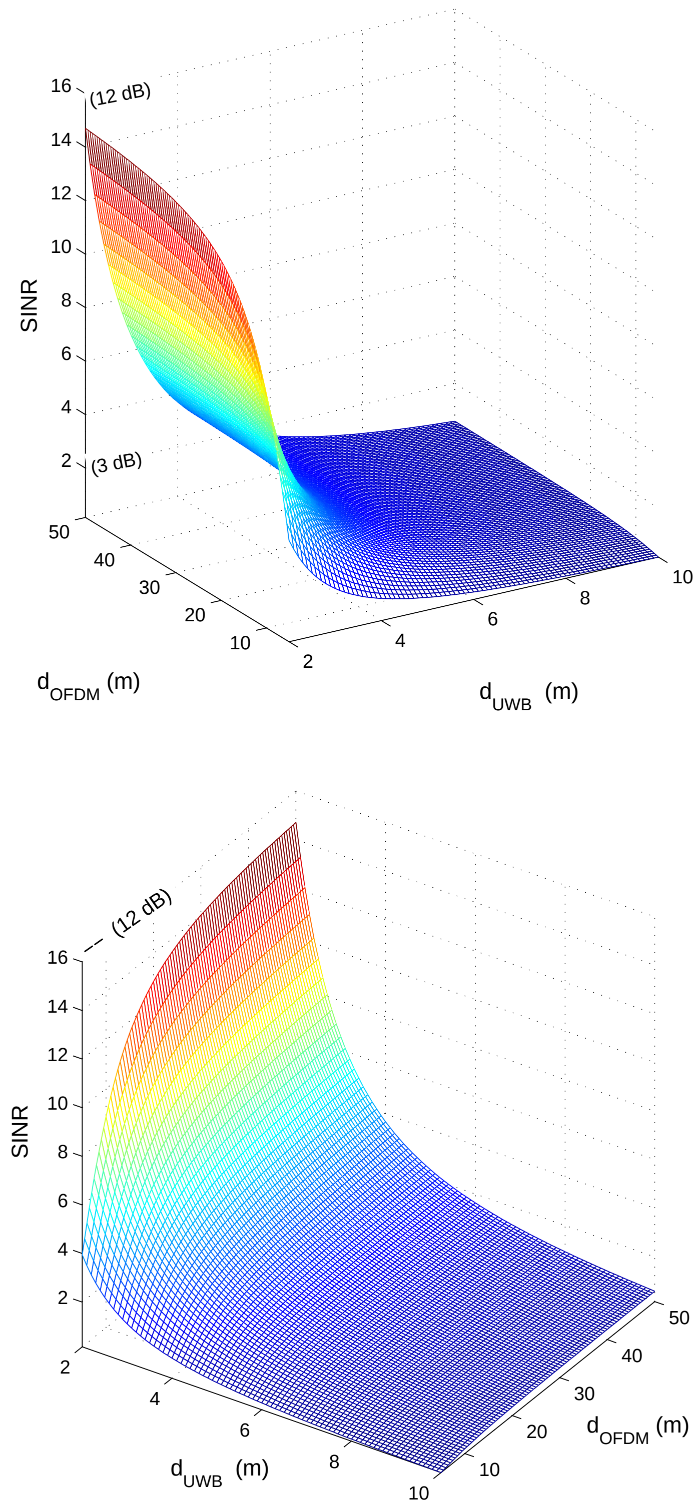


Figure 27: UWB SINR at different UWB and 802.11a source distances

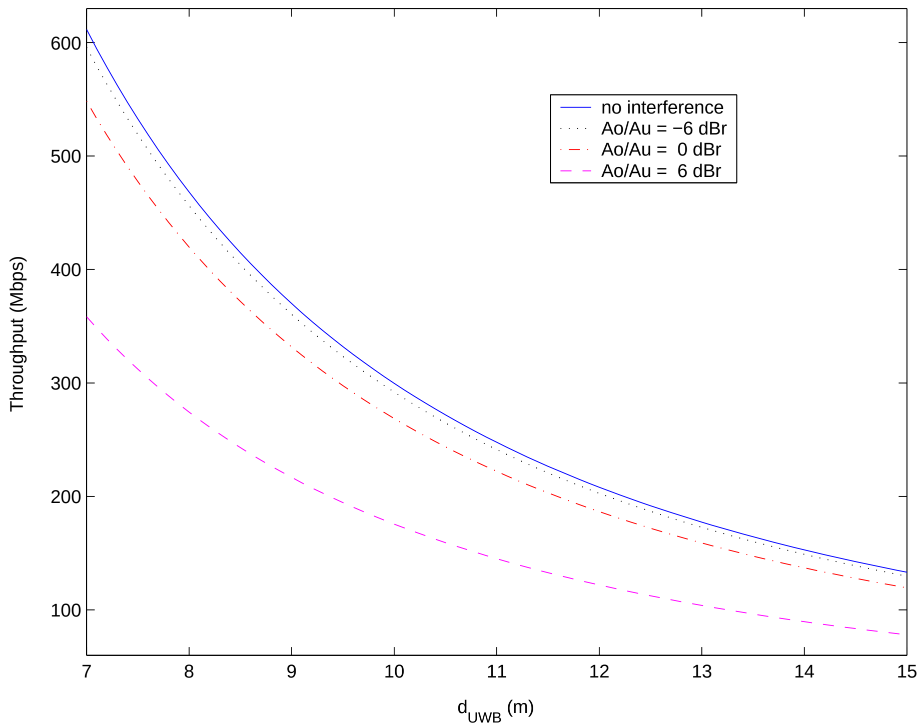


Figure 28: Throughput vs. d_{UWB} in the presence of AWGN and 802.11a interference

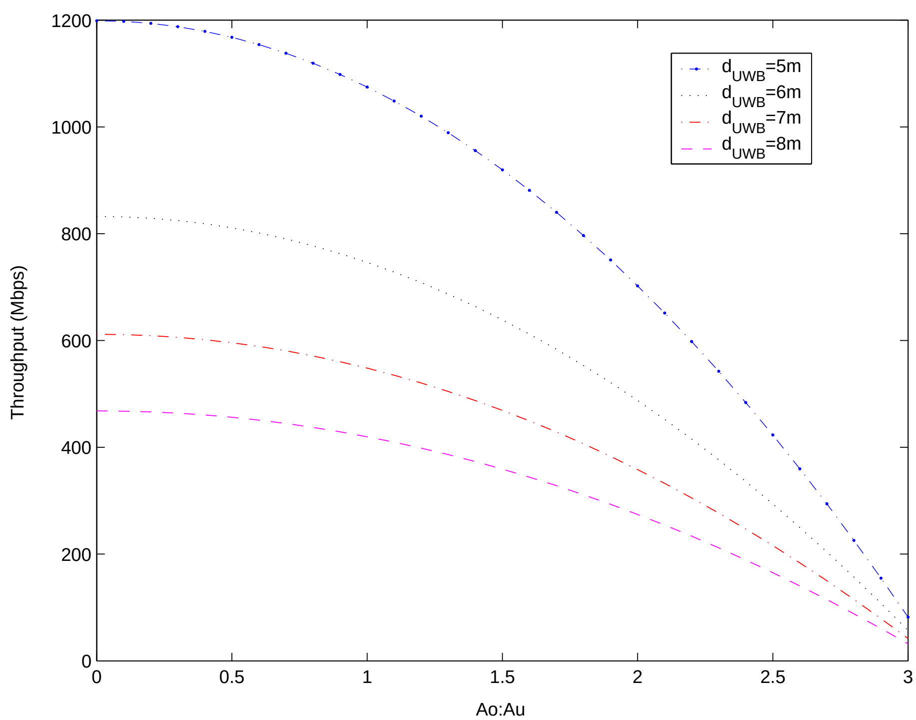


Figure 29: Throughput vs. A_o:A_u in the presence of AWGN and 802.11a interference

CHAPTER IV

HIGHER LAYER ANALYSIS AND MITIGATION OF 802.11A/UWB INTERFERENCE

As previously discussed, the interference from IEEE 802.11a on UWB systems can degrade the performance significantly. In this chapter, we introduce a novel technique in the MAC layer to reduce this interference and to enable the coexistence of both systems.

4.1 Temporal Overlap; Probability of Packet Collision

We demonstrate the coexistence of UWB and IEEE 802.11a systems in Figure 30. So far we have focussed on the frequency overlap and relative received energies of the two systems. However, there is a third dimension that must be considered: In order for the systems to interfere, there must be a temporal overlap between them as well, meaning that both system's packets must be transmitting at the same time. This was the basis for the $P(error)$ expression of (39).

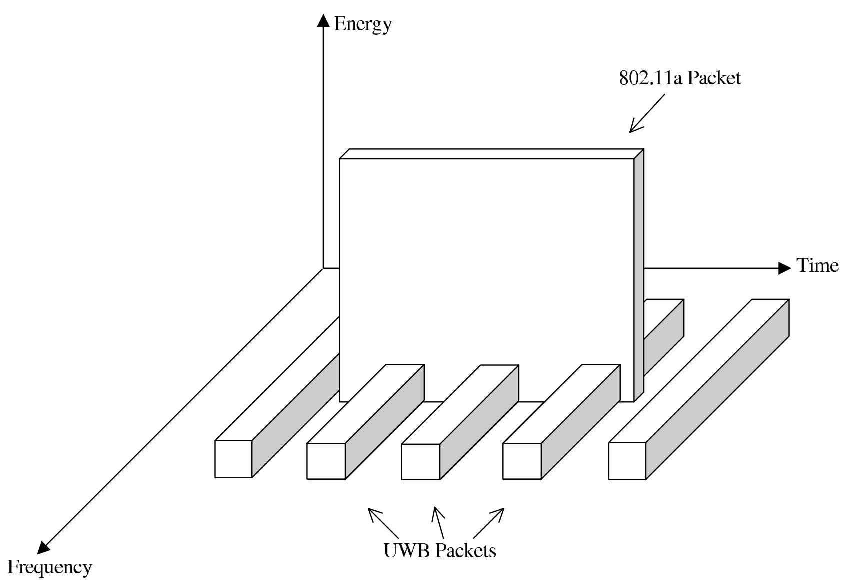


Figure 30: UWB and IEEE 802.11a Collision Scenario

The probability of signal overlap, $P(\alpha)$, can be determined based on the IEEE 802.11a and the UWB MAC protocols, or by actual system measurement. Unfortunately, due to withdrawal of UWB from 802.15.3a task force and lack of a specific MAC layer standard associated with UWB systems, we cannot provide a detailed analysis of the temporal overlap. However, it will suffice to know that there is a direct relationship between $P(\alpha)$ and the UWB system performance.

4.2 Interference Mitigation in the MAC Layer

In this section we introduce a novel technique for mitigating the interference between IEEE 802.11a and UWB in the MAC layer. Our technique provides temporal separation between UWB and 802.11a systems using the handshaking mechanisms of IEEE 802.11. To better understand this technique, we first provide a review of the IEEE 802.11 DCF mechanism below.

IEEE 802.11 DCF Mechanism: IEEE 802.11's primarily access protocol is the Distributed Coordination Function (DCF), which is based on carrier sense multiple access with collision avoidance (CSMA/CA) [7]. The CSMA/CA protocol is illustrated in Figure 31 and operates as follows: If a station wants to transmit, it first senses the medium for other active transmissions using virtual and physical carrier sensing. If the medium is not busy, the transmitting station will make sure that the medium remains idle for a required duration before attempting to transmit. If the medium is busy, then the station defers until the end of the current transmission, followed by a required idle period, at which time it will observe a random backoff time while the medium is idle, before attempting to transmit.

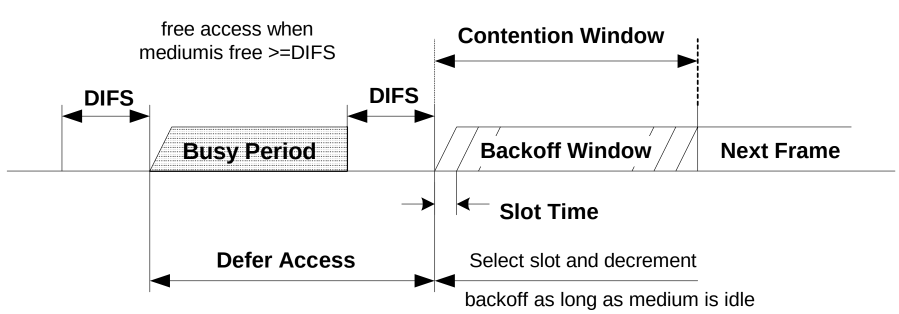


Figure 31: IEEE 802.11 CSMA/CA Mechanism

A combination of virtual and physical sensing is used to determine if the medium is busy or idle. Virtual carrier sensing uses the reservation information found in the duration field of the frames. The station's Network Allocation Vector (NAV) monitors this information. The NAV operates like a timer, starting with the value of the duration field of the last transmission, and counting down to zero. If duration field of a current frame is higher than the NAV, then the NAV stores (updates to) that value. Once the NAV reaches zero, the station proceeds to physically sense the channel. Physical carrier sensing is done by monitoring the energy level on the RF to determine if another station is transmitting or not. After the data frame is sent, if the destination correctly receives a frame, it waits for a specified short interval of time, and then sends an acknowledgment (Ack) frame back to the sender. Acknowledgment is used for all directed traffic and retransmission is scheduled by the sender if no ACK is received.

IEEE 802.11 DCF may also use a handshaking mechanism to further minimize collisions. The handshaking mechanism of the DCF scheme is shown in Figures 32 and 33. In this method, the

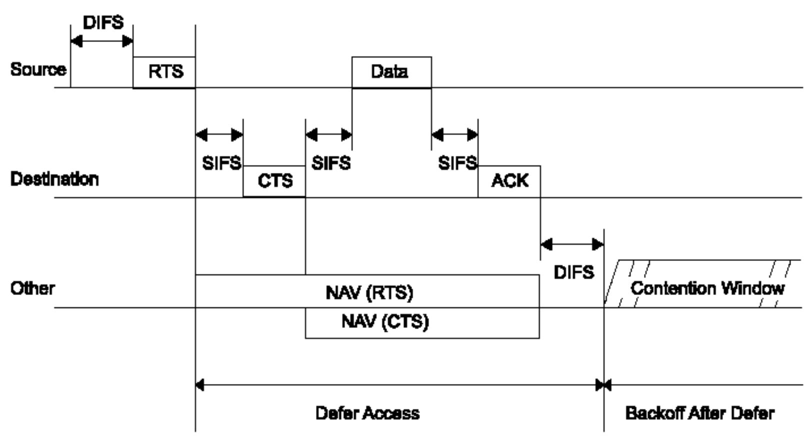


Figure 32: IEEE 802.11 DCF Handshaking Mechanism

transmitting and the receiving stations exchange short control frames, referred to as RTS (Request to Send) and CTS (Clear to Send) after determining that the medium is idle and after any deferrals or backoffs prior to data transmission. The details of this method are as follows: When a station wants to transmit a frame, it first sends a Request to Send (RTS) packet to the receiver. The receiver responds with a Clear to Send (CTS), giving the sender permission to send. The RTS and CTS packets contain a duration field that specifies the period of time needed to transmit the data frame

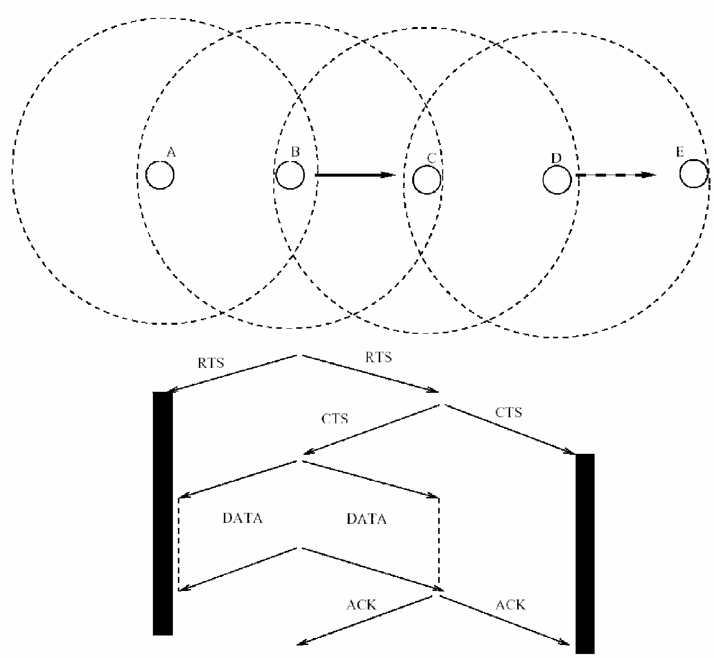


Figure 33: IEEE 802.11 DCF Handshaking Mechanism

and the Ack frame. All stations hearing the RTS or the CTS learn about the pending transmissions and update their NAV fields. Following a successful transmission, the receiver sends an Ack frame. This mechanism reduces the probability of collision, since the stations within the sender's and receiver's transmission range will hear the RTS and CTS messages and refrain from accessing the channel during the expected duration of transmission. Also, because RTS and CTS frames are short, any collision involving these frames will last a shorter time than the actual data frame, so the total overhead of collisions is reduced.

4.2.1 Proposed Mechanism

Our proposed mechanism involves cross-standard design for the ability of UWB and IEEE 802.11a to communicate with each other. The basic idea is to use handshaking control signals associated with the IEEE 802.11a standard, in order to inform IEEE 802.11a stations that the medium will be unavailable for intended periods of time. During those times, UWB stations can communicate with each other without fear of interference. Examples of feasible control messages include CTS packets, Data packets specifying a longer duration than really needed, etc. Although invasive in nature, this technique can be used as a practical and very inexpensive technique by future users who find interference to be a serious problem; consider a patient using his/her IEEE 802.11a Internet connection while having his vital signs monitored wirelessly using an UWB technology, or a user surfing the web using IEEE 802.11a while watching a TV program broadcast from the next room using UWB.

As an embodiment of this idea, we may introduce a proxy that is capable of sending IEEE 802.11a control messages, alerting the IEEE 802.11a stations to hold off their transmissions for a specified period of time in order for UWB transmissions to take place. The proxy may do this at regularly scheduled periods, specific times based on channel conditions and traffic characteristics, or upon receiving channel reservation requests from the UWB station(s). The scheduling can be decided based on a umber of factors including the ratio of the number of UWB stations to the number of IEEE 802.11a stations in the BSS, the priority of different traffic streams in the two systems, channel conditions, error rates, QoS requirements, etc. Our device may choose to follow the CSMA/CA protocol specified by the 802.11 DCF, or it may act in an aggressive manner by transmitting it's control messages as soon as the channel becomes available (not advised). This device may work independently (e.g., the user can enter the ratio of the number of different stations present or select specific profiles for their application needs), or it may communicate with the UWB station(s) wirelessly or by other means.

Many variations of our technique can be used. Consider that many wireless units, such as laptops, PDA's and even mobile phones, are begining to incorporate a number of different wireless technologies. If, for example, both UWB and 802.11a are incorporated into the same device, it is possible to not only negotiate the use of the different technologies internally within the device, but to also mediate the wireless channel use for other devices in range, by the use of similar (handshaking) control messages. For example, if the laptop is receiving a real-time stream from a nearby UWB unit, it can alert other 802.11a stations nearby (by sending 802.11a control messages) to backoff at specific times in order to support the UWB transmission. Furthermore, if we have a case of several devices (e.g., laptops) using both technologies, we may have a collaborative mechanism, where the two systems exchange information with each other and negotiate the use of the channel; the UWB stream may request transmission of 802.11a control messages clearing the channel for specific periods of time for its use, while 802.11a streams may request transmission of UWB control messages during those times, alerting other UWB stations of pending 802.11a transmissions. Although the threat of interference from UWB on 802.11a systems is less, by doing this, we can further reduce the interference, reduce the use of energy and computational resources, reduce the number of UWB retransmissions, and enable the 802.11a stations to negotiate the channel use as well.

4.3 Simulation and Results/Observations

To illustrate our technique we introduce a proxy (referred to as "CTS Generator") that is capable of sending IEEE 802.11a CTS messages at specific intervals using CSMA/CA mechanism similar to IEEE 802.11a. When the other IEEE 802.11a stations in the range hear the CTS messages, they delay their transmissions, clearing the channel for UWB communications.

We use the Georgia Tech Network Simulator, GTNets [56], which is a a full-featured network simulation environment based on C++. Although the current version of GTNets did not have a built in simulation model for IEEE 802.11a, we built the 802.11a model and added it to the current library for future use. The parameters used in our simulation/model are specified in table 6.

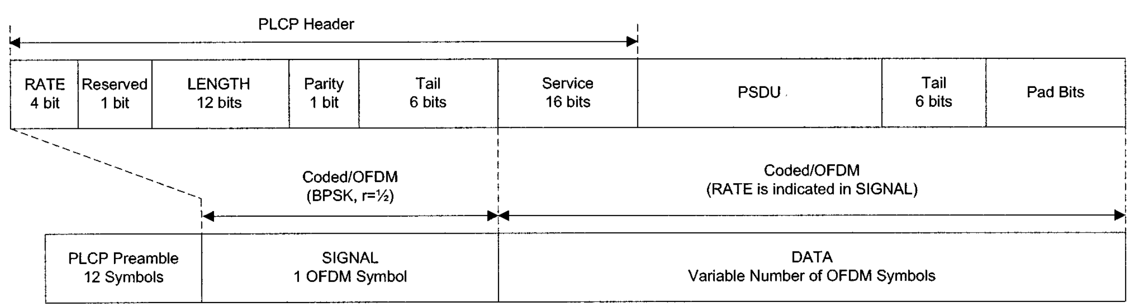


Figure 34: PDU Frame Format of IEEE 802.11a [3]

For our simulation we use the system topology shown in figure 35. The figure shows an (IEEE)

Table 6: IEEE 802.11a Parameters used in our Simulations

Parameter	Value
Slot time	9 μs
SIFS time	16 μs
DIFS time	34 μs
Propagation delay	1 μs
Transmission time for PHY Preamble	16 μs
Transmission time for PHY Header	4 μs
Transmission time for a symbol	4 μs
Min Backoff Window size (CW_{min})	15 $slot\ times$
Max Backoff Window size (CW_{max})	1023 $slot\ times$
Payload	512 $bytes$
MAC overhead	28 $bytes$
SNAP header	8 $bytes$
RTS packet size	20 $bytes$
CTS packet size	14 $bytes$
Ack packet size	14 $bytes$
Data rate	54 $Mbps$
Basic rate	6 $Mbps$

802.11a transmitter which follows a 50 m trajectory (shown by dark arrow) in an indoor environment, as it communicates with the 802.11a receiver. We demonstrate the amount of interference received by a neighboring UWB receiver who is communicating with a nearby UWB transmitter. We simulate the system behavior with, and without, the presence of the "CTS Generator" device which we have proposed in the previous section. In our simulation we use a data packet payload of 512 bytes. The frame format for an IEEE 802.11a packet is shown in figure 34. IEEE 802.11a permits much larger frame sizes, however, we focus on frame sizes below 1500 bytes. This is because most access points connect to existing networks with Ethernet, and therefore limit the payload size to the maximum Ethernet payload size of 1500 bytes. In fact, this simple precaution is required to obtain Wi-Fi certification [57]. In addition to the parameters of table 6, a transmit PSD of -41 dBm/MHz (7.413×10^{-5} mW/MHz) was used for UWB, and a PSD of 2.5 mW/MHz was used for 802.11a. A free space propagation model was used, and antenna gains of 0 dBi were assumed for both systems. A constant bit rate application was used, leading to 15 Mbps of traffic at the physical layer. This was pretty close to the saturation point for our system. We choose to simulate the entire trajectory over a one second period in order to reduce the density of our plots for discussion purposes. This will not affect the power and throughput results of our simulation in any way.

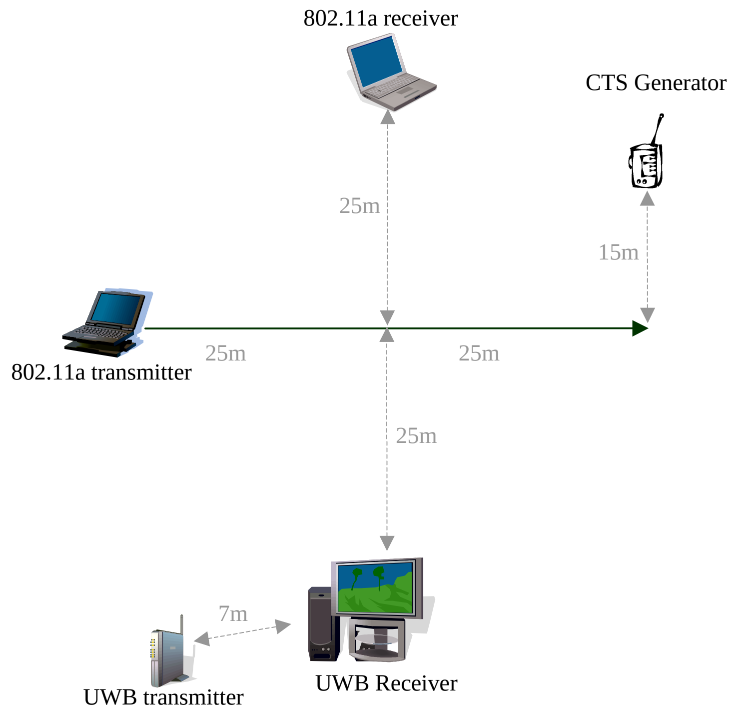
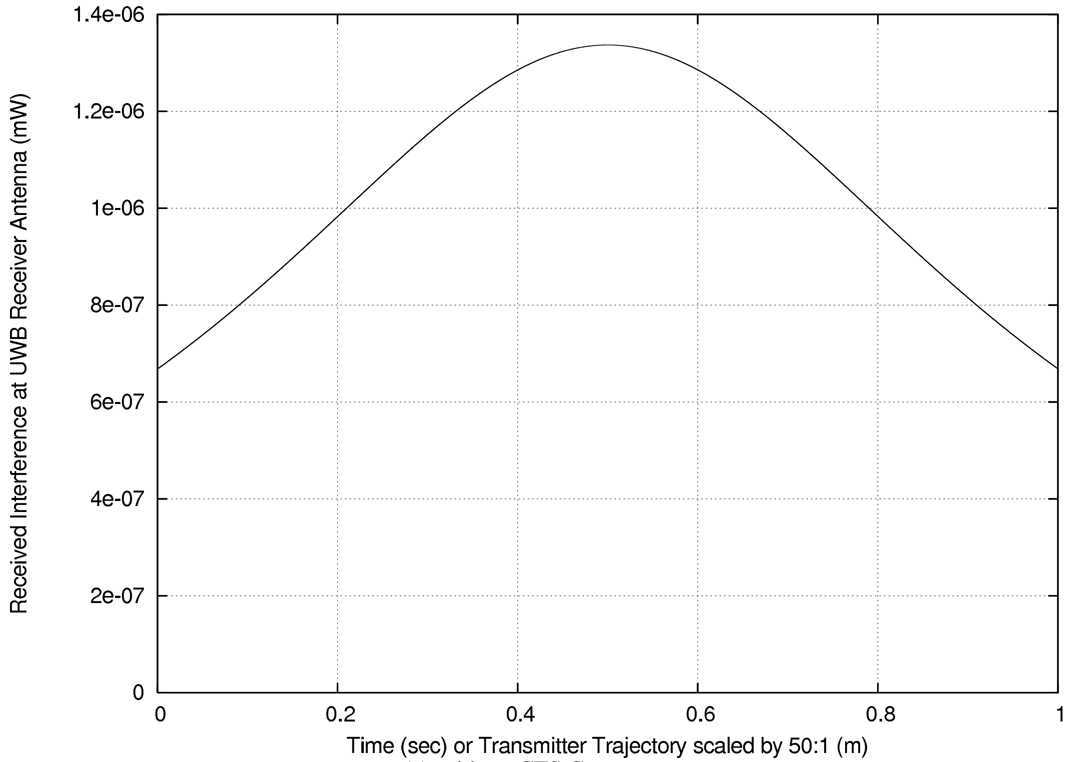
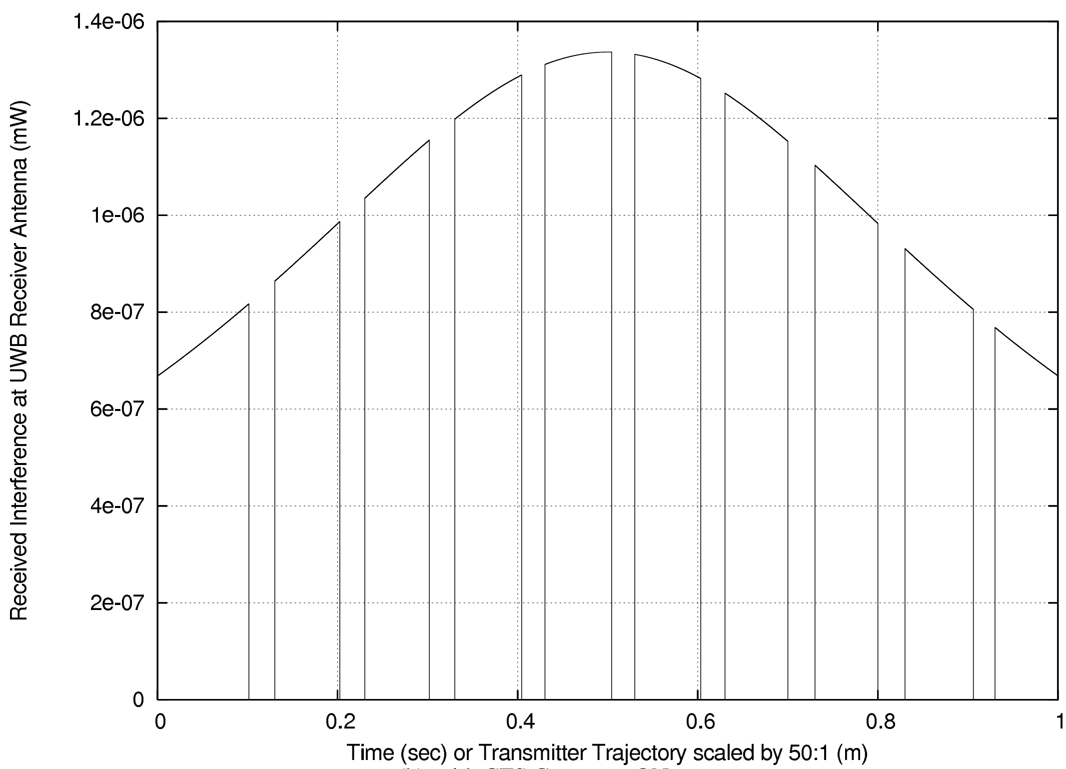


Figure 35: Simulation Model

Figure 36 (a),(b) shows the received interference power at the UWB receiver antenna without the CTS Generator present and with the CTS Generator present (on). It can be seen that the received interference is the highest in the middle of the simulation/trajectory, where the 802.11a transmitter is closest to the UWB receiver. Figure 36(b) demonstrates that during the periods when the CTS messages are sent by CTS Generator, the 802.11a transmitter refrains from transmitting, leaving these periods available for UWB use. Within the simulation model we built, we can specify the CTS intervals and the duration field for CTS messages (limited by the maximum allowable duration), as well as the number of consecutive CTS messages. In the figure specified, we are shutting off about $\%20$ $(20ms)$ of the 802.11a transmissions at $0.1s$ intervals and allocating them for UWB use.

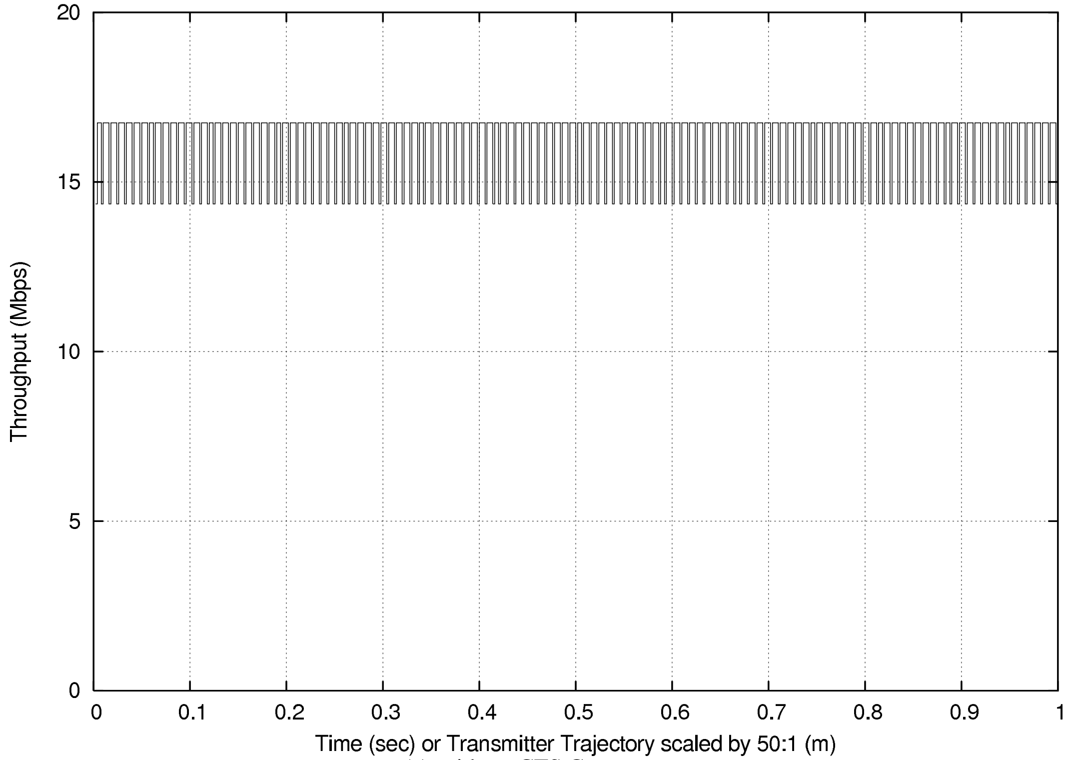


(a) without CTS Generator

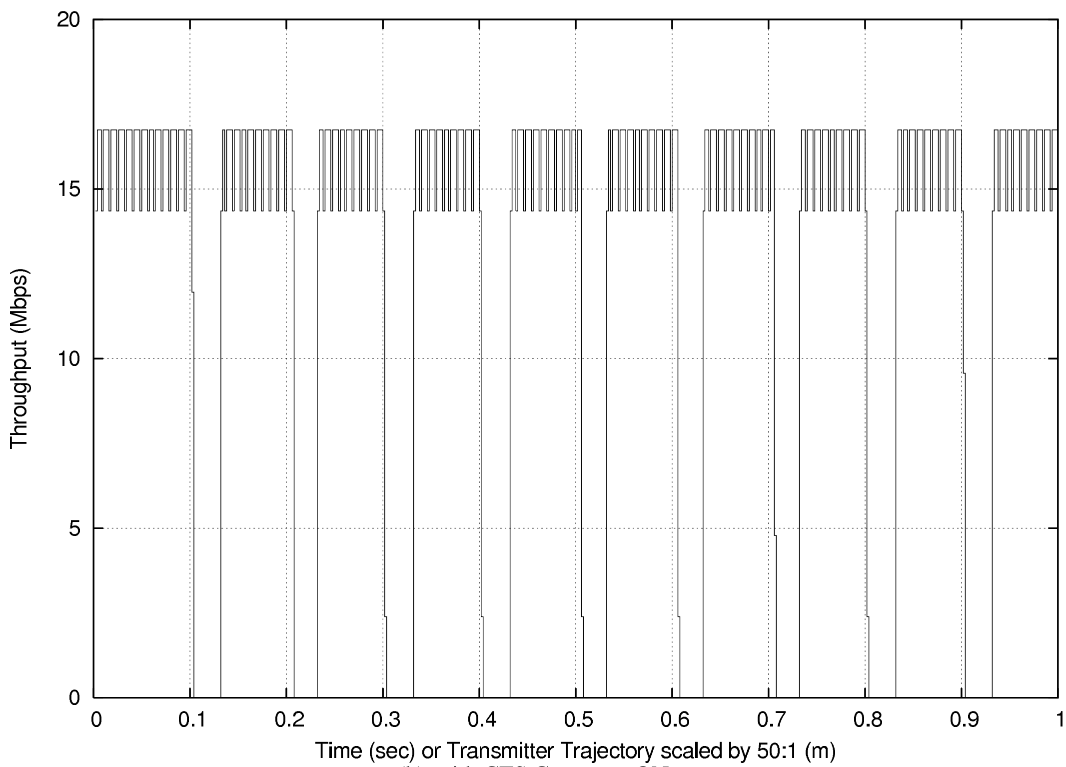


(b) with CTS Generator ON

Figure 36: Received Interference Power at UWB Receiver Antenna



(a) without CTS Generator



(b) with CTS Generator ON

Figure 37: Throughput of the IEEE 802.11a System

Figure 37(a) shows the throughput of the IEEE 802.11a system prior to addition/operation of the CTS Generator. Figure 37(b) shows the throughput as a result of our CTS Generator device. Again, it can be seen that the throughput drops to zero during the periods requested by CTS, and that the total 802.11a throughput is cut by about $\%20$ in order to accompany the UWB stations' transmissions. The small variations in the throughput are due to the short time duration during which our "instantaneous" throughput was collected. We use the actual trace file created by the simulation and count the number of data packets (and corresponding number of bits) received in each of our defined time periods ("bins"). For example, in figure 37 we use a time period (bin size) of 2 ms. If we increase this time period to 8 ms, we get the results plotted in figure 38. The periodic (small) variations in throughput have averaged out, but the graph does not represent the throughput in relationship to the time axis as accurately.

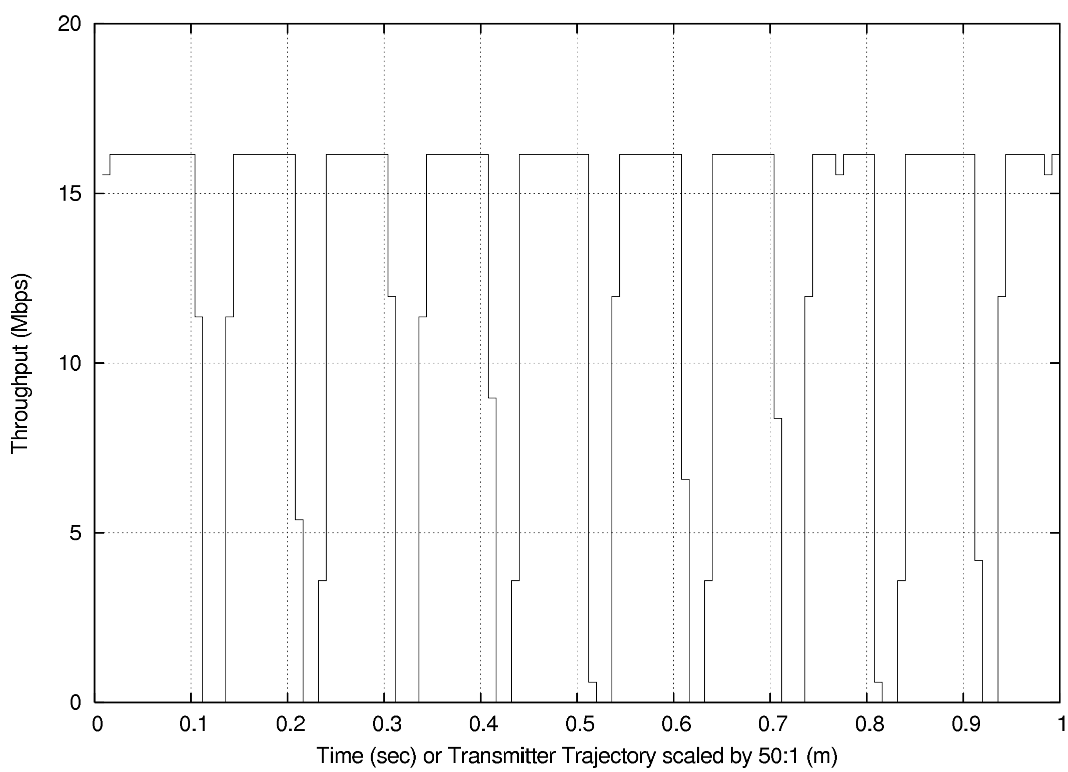


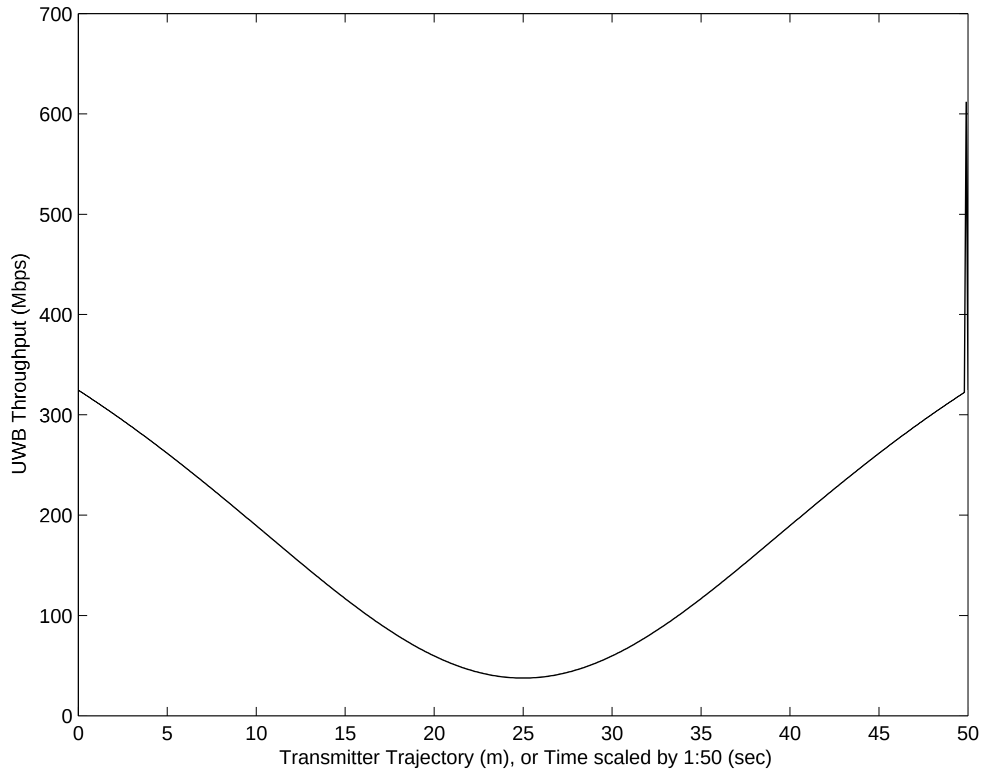
Figure 38: Throughput Plot with Larger Bin Size Used, CTS Generator ON

In order to check the results of our simulation, consider the following approximation: In addition to our payload data (512 bytes), there are 36 additional bytes of data (28 bytes MAC header + 8 bytes SNAP encapsulation header) added in the encapsulation process, making the total size of the MAC frame 548 bytes. The OFDM encoding used by IEEE 802.11a adds six bits for encoding purposes, making the total frame length equal to 4390 bits. At 54 Mbps, each symbol encodes 216 bits, so our frame can be encoded in 21 symbols. The 802.11a RTS, CTS, and ACK, each require one symbol. Each frame is prepared for transmission in the air with a $20\mu s$ header to synchronize the receiver, followed by the frame symbols, each requiring $4\mu s$ of transmission time [57]. In other words, we require $20\mu s + (21 symbols)(4\mu s/symbol) = 104\mu s$ to transmit a data frame, and $20 + (1)(4) = 24\mu s$ to transmit a control (RTS, CTS, ACK) frame. For a full cycle of RTS-CTS-Data-Ack handshaking mechanism, we need a minimum of:

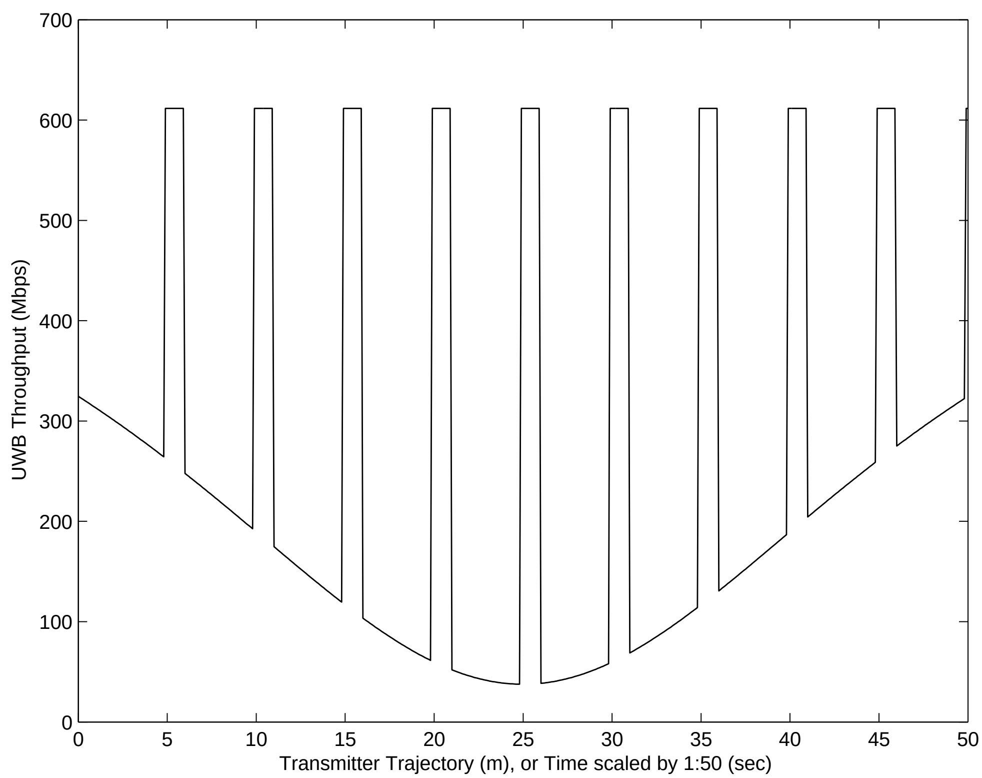
$$\begin{aligned} &DIFS\,(34\,\mu s) + RTS\,(24\,\mu s) + SIFS\,(16\,\mu s) + CTS\,(24\,\mu s) + SIFS\,(16\,\mu s) \\ &\quad + DATA\,(104\,\mu s) + SIFS\,(16\,\mu s) + Ack\,(24\,\mu s) \;=\; 258\,\mu s \end{aligned} \tag{41}$$

So we need 258 μs to transmit 4390 bits, corresponding to a throughput of $4390\ bits/258\ \mu s = 17\ Mbps$. Considering other delays unaccounted for in the above expression, our simulation results are reasonable, and consistent with throughput figures of [3]. Please note that increasing the payload size would increase the available bandwidth significantly, since the protocol overhead for each packet is fixed and relatively large.

Due to lack of a widely accepted UWB standard, we chose to evaluate the theoretical maximum throughput (bit rate) at the UWB receiver, using the received UWB and IEEE 802.11a powers and the UWB effective bit energy. This was done using MATLAB [58]. In addition to the aforementioned parameters and assumptions, a noise figure of 6 dB, a target BER of 10^{-3}, and an implementation margin of 2 dB were assumed. The results are shown in Figure 39. Even though the UWB transmitter is only 7 meters away from the UWB receiver, the dramatic effect of an IEEE 802.11a interferer 35-25 meters away can be seen. Again, we demonstrate the throughput with and without the presence of our CTS generator. Observe that with the presence of the CTS Generator the instantaneous maximum throughput can increase by as much as 574 Mbps during the reserved UWB time slots. Because of UWB's potentially high data rates, this means that a temporary sacrifice of IEEE 802.11a throughput can lead to a much higher gain in the UWB throughput, thereby providing an overall gain for the entire system. We discuss an example of this when mitigating the interference between an IEEE 802.11a data application and an UWB HDTV application in chapter 5.



(a) without CTS Generator



(b) with CTS Generator ON

Figure 39: Throughput of the UWB System

CHAPTER V

IMPLICATIONS TO WIRELESS SERVICES IN THE HOME

In chapter 2 we introduced a typical wireless home network and listed some of the applications that will be present in the future wireless home/office environments. In this chapter we address the UWB technology and IEEE 802.11a technologies and their coexistence from an application driven point of view, thereby closing the loop between some of the applications discussed in chapter 2 and the issues discussed in chapters 3 and 4. In section 5.2 we present a simple example of how an UWB HDTV application may be supported over a channel degraded by 802.11a interference.

A number of issues characterize the wireless network and contribute to the overall user experience and satisfaction. These include: bit rate, loss, latency, jitter, power consumption, security/privacy, complexity and cost, and always-on characteristics. These were discussed in great detail in chapter 2. Bit rate, loss, and latency (and jitter) are some of the most important QoS parameters and their relationships to the different classes of multimedia applications were outlined in table 2.

Table 7 provides a qualitative mapping between some more applications and a broader set of the dimensions discussed. Note that within short distances (less than 10 meters), UWB technology can support most of these capabilities. Although the UWB mobile device is not connected to a continuous power supply, given the the low power consumption of UWB devices, the battery can last long enough to support some ”always-on” applications.

As a comparison of the different technologies in regard to speed, please consider a sample listing of download times for different media at different access speeds (bit rates) in Table 8. For example, to download an audio album using a 64kbps connection, it will take 4325 seconds (72 hours), compared to only 5 seconds when using a 54 Mbps connection, such as IEEE 802.11a or IEEE 802.11g.

Table 7: Service Capabilities/Characteristics and Application Classes [1]

Capability	Application
Large downstream bandwidth	Streaming content (e.g., video)
Large upstream bandwidth	Home publishing
Always-on	Information appliances
Low latency	VoIP, interactive games

A 480 Mbps bit rate, such as UWB, can offer an even richer experience; in order to download a 1000 MB video over a 54 Mbps connection, it will take 148 seconds (almost 2.5 hours), whereas on a 480 Mbps connection it will only take 17 seconds.

Table 8: Seconds to Download Various Media Types at Different Access Speeds

Media	Typical file-size (MB)	64 kbps	54 Mbps	480 Mbps
Image	0.1	12.5	0.01	0.002
Audio (Single)	1.9	237.5	0.28	0.032
Audio (Album)	34.6	4325.0	5.13	0.577
Video	1000.0	125000.0	148.15	16.667

A number of audio, image, and video coding standards are presented in tables 9, 10, and 11. Explanation of these coding standards are presented in appendix B. Signal compression and coding plays a very important role in supporting high bit rate applications and achieving a higher broadband margin. The broadband margin is defined as the radio of total bit rate, as seen by the user, to the bit rate needed by an application. Signal compression reduces the bit rate needed for an application, thereby enabling the support of many media over wireless networks that would not have been possible otherwise. Within the range of UWB PAN, each of the tabulated applications can easily be supported over an UWB connection. In fact the high bandwidth (throughput) of UWB technology enables support of a multiple number of these applications without threatening other systems operating in the same frequency bands.

Table 9: Audio Compression Standards [1]

Audio Coding Standard(s)	Primary Intended Applications	Bit rate
MPEG-1 kayer-1/2 and layer-3 (MP3)	Compression of wideband audio (32, 44.1, and 48 kHz sampling rates)	128 kbps for MP3 stereo
MPEG-2 AAC	Improved compression compared to MP3; improved joint stereo coding	96 kbps for stereo
MPEG-4 natural audio (AAC, CELP, TwinVQ, etc.))	Coding of natural speech and audio at a wide range of bit rates and audio bandwidths, and new functionalities such as scalability and error resilience	Speech at 2-24 kbps; Audio at 8-64 kbps
MPEG-4 synthetic audio (TTS,SA)	Text-to-speech; downloadable signal processing algorithms for synthesizing audio at the receiver and applying postprocessing effects to natural and synthetic audio objects to create the audio scene.	Variable

In addition to the bit requirements, different application have different delay and packet loss (or packet error rate or frame error rate) requirements. Figure 40 presents a good example of some of these requirements. For example, for real-time conversational voice, one-way end-to-end delay of less than 100 ms is ideal; delays of up to 400-500ms are acceptable, but come with some degradation. For real-time conversations voice, the acceptable maximum packet error rate (PER) is 3%. This translates to a BER of 7.3e-6 for a packet size of 512 bytes and a BER of 2.5e-6 for a packet size of 1500 bytes.

5.1 UWB and IEEE 802.11a Coexistence

We've demonstrated the bit rate (throughput) at the 802.11a receiver in figure 37. Observe that even in the absence of interference and multiple 802.11a stations (multiple access contention), the throughput is much less than the maximum 54 Mbps, due to a number of factors, including the physical layer overhead and the protocol overhead. Moreover, the wireless medium is prone to

Table 10: Image Compression Standards [1]

Image Coding Standard	Primary Intended Applications	Bit rate
JPEG	Coding of continuous-tone images	0.5-1.0 bit/pixel
JPEG-LS	Lossless compression of continuous-tone images	Highly variable
JPEG-2000	Coding of continuous-tone images, various forms of scalability, browsing over the Internet, multichannel and high-bit-depth images	0.1-0.5 bit/pixel

Table 11: Video Compression Standards [1]

Video Coding Standard	Primary Intended Applications	Bit rate
H.261	Videotelephony and teleconferencing over ISDN	p $\times$ 64 kbps
MPEG-1	Video on digital storage media (CD-ROM)	1.5 Mbps
MPEG-2	Digital Television	2-20 Mbps
H.263	Video telephony over PSTN	33.6 kbps and up
MPEG-4	Object-based coding, synthetic content, interactivity, video streaming	Variable
H.264/MPEG-4 Part 10 (AVC)	Improved video compression	10s of kps to 10s of Mbps

degradation due to path loss, fading, and interference from other devices. The goodput (application level throughput) is expected to be even less.

For example, assume that we are supporting a number of UDP application(s) (e.g., VoIP) over 802.11a. The packet is divided into UDP frames (packets), and each UDP segment is inserted into an IP datagram, which is then inserted into our 802.11a MAC frame. The overheads include: 8 bytes for the UDP header, 20 bytes for IP header, 36 bytes for MAC and SNAP encapsulation headers, and six bits for OFDM encoding. So, assuming a MAC payload of 512 bytes, and ignoring all other/protocol

Class	**Interactive**	**Responsive**	**Timely**	**Non-critical**
Delay	<< 1 sec	~ 2 sec	~ 10 sec	>> 10 sec

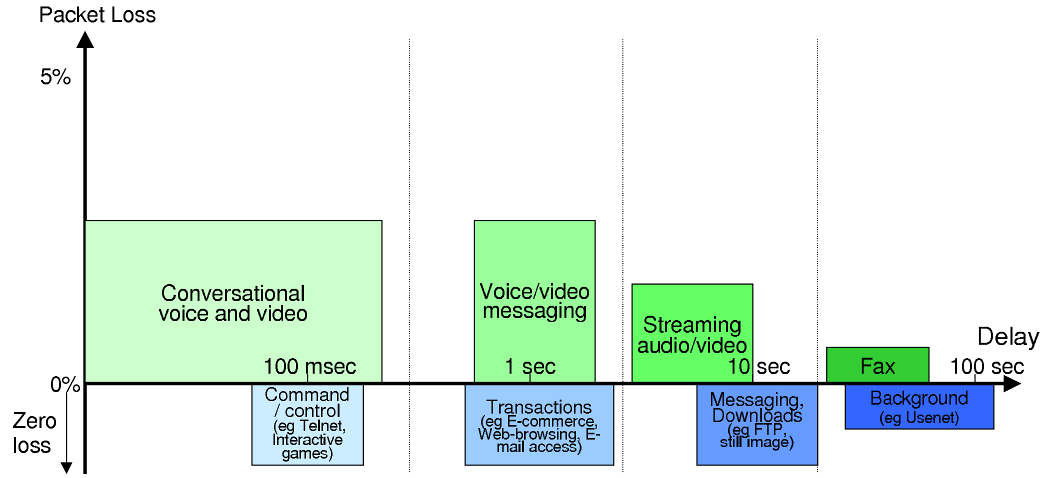


Figure 40: Packet Loss and Delay Requirements of Different Classes of Applications [4]

overheads, the maximum possible goodput would be: $(512 - 8 - 20)\ /\ (512 + 36 + 6/8)\ =\ 88\%$ of the MAC throughput. This is when neglecting any other protocol overheads. In fact the actual throughput (goodput) available to the higher layer applications is usually much less. This is enough to support a few applications, but not all the needs of future wireless home/office networks. As another example, according to the simulation in [4] for robust video transmission over IEEE 802.11b (11 Mbps), the average available bandwidth (maximum throughput) at the application layer for such application is only 4.5 Mbps. The authors of [59] have similar findings for throughput of voice over IP (VoIP) and UDP traffic in 802.11b networks.

In order to support other applications within the home, none of the current technologies, alone, suffices. We, therefore, envision a future wireless home where a number of technologies coexist together and complement each other. For example, a number of short range, high speed audio visual applications can be supported over UWB. IEEE 802.11 wireless LANs can in turn support additional data and lower speed (but higher range) applications. In figures 28 and 29 we demonstrate the UWB bit rate as a function of the distance between the transmitter and the receiver. It can be clearly seen that at shorter distances (e.g., less than 15 meters), maximum physical layer throughputs of hundreds of mega bits per second can be supported, thereby providing support for multiple audio and visual transmissions.

We have, however, shown that in the presence of IEEE 802.11a interference, the UWB transmissions can be greatly degraded. In figure 39 we show the degradation of UWB throughput from 611.6 Mbps to as low as 37.6 Mbps as the 802.11a transmitter moves closer to the UWB receiver (25 m away from the UWB receiver). This is the raw throughput at the physical layer, corresponding to even a lower goodput at higher layers. This will have a serious impact on our applications, especially real-time streaming media.

Telemedicine will be an important application in the (future) wireless home. Telemedicine applications are very varied and can utilize a number of services previously mentioned, including sensory information, audio, video, and still images, etc. An example of this is discussed in Appendix A, where we utilize the GTWM [60] to monitor a person's electrocardiogram (ECG) remotely while maintaining an audio communication with the person as well. More elaborate examples would include other vital signs as well as two-way communication and video. Such applications would require anywhere from a few kbps to 100's of kbps in the downstream and anywhere from 100's of kbps to 1000's of kbps in the upstream. Furthermore, telemedicine applications tend to have large sensitivities to loss, delay and jitter, requiring certain QoS guarantees in these criteria. Consider a person having his vita signs transmitted wirelessly over an UWB connection to a nearby station. We simply cannot risk degradation and loss of these signals due to a nearby 802.11a transmission. Therefore, the use of a device similar to our "CTS Generator" becomes increasingly important and a necessity in such environments. Although the applications tend to have relatively low to moderate bit rate requirements, their sensitivities to loss, delay and jitter, require that we schedule periodic gaps in 802.11a transmissions in order to provide guaranteed transmission of our UWB/telemedicine data. The allocation of the bandwidth and the timing and duration of the gaps are application-specific, but rather simple, following a similar approach to that shown in the next section.

In the next section we discuss an HDTV application, and show a simple design example of how we would mitigate the effects of such interference based on the specific application parameters.

5.2 HDTV Example

Consider a house where HDTV video (e.g., from a media source such as DVD or computer or cable) is being transmitted to different rooms. The video is transported over an IP-based home network with highly unpredictable and time-varying throughput and delay. Consider again, that somewhere nearby (in the house or outside of the house, from a neighbor), an IEEE 802.11a system is operating, causing interference at the UWB receiver. For purposes of this example, consider the scenario where the UWB transmitter-receiver separation is $10\ m$ and the distance between the 802.11a transmitter and the UWB receiver is $35\ m$.

Referring to the video coding standards in appendix B.3, assume we use an HDTV video with MPEG4/H.264 compression requiring 8-10 Mbps at the application layer. With the addition of error protection codes and different overheads at the lower layers (e.g., UDP, IP, MAC and PHY overheads), this translates to about 13-16 Mbps at the Physical layer.

Consider a scenario where the UWB transmitter-receiver separation is 10m. Our desired bit error rate is at least 10^{-6}. Without the presence of interference (such as multi-user interference or interference from other systems), the maximum throughput of our UWB system at the PHY layer is 299.7 Mbps, enough to support several HDTV streams. Consider the case when an IEEE 802.11a interference source is present at 35 m from the UWB receiver. The throughput immediately drops to 6.8 Mbps, which is no longer sufficient for our HDTV system.

Now, let us place a CTS Generator within the BSS of the 802.11a transmitter. In order to support the additional required 16-6.8=9.2 Mbps, we need to allocate $9.2/(299.7 - 6.8) = 3.14\%$ of the 802.11a transmission time to UWB transmissions. How we allocate the additional transmission time will affect the delay experienced by the HDTV receiver (as well as the delay performance of the 802.11a system). For example, we could allocate (not recommended)a block of 9.42% of the channel every three seconds. However, this is not recommended, since most of the UWB (HDTV) traffic would be delayed by a few seconds (especially, since most of the UWB throughput will occur during the times that the 802.11a system is held suppressed), and the performance of 802.11a stations would be uneven as well. In fact There is a maximum delay that is tolerable for the system (usually up to 500 ms). The delay is determined in part by the interval that the receiver chooses to wait (queue the received packets) before actually decoding and playing the video. This time interval is determined based on the maximum tolerable delay perceived by the viewer. The incoming video frames are buffered in order to reduce the possibility of underflow and prevent interrupted display as a result of jitter or packet delay.

To consider the delay properties, consider cable TV transmission over HDTV: A delay of up to 500 milliseconds is acceptable, and in fact, recommended, in order to deal with possible jitter and unexpected burst errors in the wireless channel. Now consider what happens if a person wants to flip through different channels. Any delay of more than one second can be quite annoying. A better approach would be to spread the utilization of the bandwidth evenly, for example reserving approximately 1 msec of the channel at every 31 milliseconds.

CHAPTER VI

CONCLUDING REMARKS

6.1 Summary of Results

Our research was motivated by the study of UWB technology and its coexistence with IEEE 802.11a within the wireless home/office environment. UWB is a promising wireless PAN technology and complements the already popular wireless LAN/PAN technologies such as IEEE 802.11 and Bluetooth. IEEE 802.11a operates in frequency bands that overlap UWB's frequency spectrum, raising the potential for interference between the two systems. The major contribution of our research was to provide a coexistence framework for UWB and IEEE 802.11a by characterizing the interference between the two systems and offering a unique solution for mitigation of the interference for home wireless applications:

- Characterization of interference from UWB on IEEE 802.11a systems
- Characterization of interference from IEEE 802.11a on UWB systems
- Mitigation of Interference using temporal separation in the MAC layer
- Implications to Wireless Home Services

6.1.1 Characterization of interference from UWB on IEEE 802.11a systems

We have presented analytical and simulation results to demonstrate the interference of nearby UWB stations on IEEE 802.11a systems. We demonstrate using SINR, BER, and throughput analysis, that the interference from UWB to IEEE 802.11a stations is very weak and in most situations, negligible.

6.1.2 Characterization of interference from IEEE 802.11a on UWB systems

As discussed in section 3.1, the interference between IEEE 802.11a and UWB is asymmetrical. Since the interference from IEEE 802.11a on UWB systems is a lot more significant than the interference of UWB on IEEE 802.11a systems, we dedicated a good portion of our research to analysis of this interference. Our work in modeling the interference from IEEE 802.11a on UWB was among the earliest of its kind. We developed detailed analytical models and closed form expressions for a number of UWB modulation schemes, including TH-PPM, TH-PAM, and DS-PAM. Our techniques can be applied to other modulation schemes or other UWB systems. Our simulations provide further understanding of the system behavior through SINR, BER, throughput, and other forms of analysis (e.g., distribution functions). Our results consistently show that IEEE 802.11a interference can have a very significant effect on UWB systems and must be mitigated or eliminated for successful operation of UWB devices. Our models have been referenced and our techniques replicated in a good number of publications by the research community.

6.1.3 Mitigation of Interference using temporal separation in the MAC layer

In the earlier parts of our work, we focussed on frequency overlap and power characteristics of the two systems. In this portion of the research we discuss the effects of temporal overlap (packet collision) between the two systems. We introduce a novel technique in the MAC layer to reduce this interference using temporal separation. We simulate our technique and show that it can be very effective in mitigating the IEEE 802.11a interference and enabling the coexistence of both systems. We introduce many variations of our technique that can used as unique, simple and inexpensive solutions in reducing/eliminating the interference.

6.1.4 Implication to Wireless Services in the Home

We have discussed different wireless home network design issues and application characteristics throughout the thesis. We've also provided examples of the UWB and 802.11a technologies from the perspective of home and office application classes and their required QoS. We further elaborate on the coexistence issue and interference mitigation by introducing realistic examples, such as HDTV and telemedicine. The telemedicine discussion arises from our previous work on wireless transmission of vital signs using the Georgia Tech Wearable Motherboard. This work is explained in great detail in Appendix A, and has received a lot of attention from the media and academic community.

6.2 *Suggestions for Further Research*

6.2.1 Accurate Modeling of the Temporal Overlap between the Two Systems

In our derivations of the interference between the two systems, we mainly focussed on the frequency overlap and the relative energies of the two systems, specifying an upper bound (worst case scenario) for the interference. As mentioned in section 4.1 and reflected in (39), however, the actual interference is a function of the temporal overlap between the systems as well.

The probability of temporal overlap, can be determined based on the specific UWB and IEEE 802.11a MAC protocols. Depending on the actual UWB MAC protocol used (whether proprietary or resulting from any future standardization efforts), the probability of temporal overlap between the two systems can be modeled, providing further insight into the nature of the interference. Moreover, by doing measurements in appropriate environments, the model can be further fine tuned for more realistic results.

6.2.2 Application of Our Temporal Separation Technique to Other Systems

In section 4, we provided generalized approaches to dealing with 802.11a interference using inter-technology or inter-standard handshaking in order to achieve temporal separation between the interfering systems. Similar techniques may be applied to other technologies incorporating handshaking in order to deal with interference, for example mitigating the interference between IEEE 802.11b and Bluetooth systems.

6.2.3 Variations of Approach

In section 4, we provided a number of different approaches to dealing with 802.11a interference on baseband UWB systems. Although we presented a number of ideas, we did not develop them in full detail. Examples include collaborative efforts in mesh networks, taking advantage of 802.11a protocol to optimize the system, determination of transmission/backoff times based on channel conditions, error rates, priority of traffic, numbers of- and distances between the different UWB and

802.11a stations, etc. These techniques can be further investigated and built upon to provide a number of useful applications.

APPENDIX A

COMMUNICATION OF VITAL SIGNS OVER A WIRELESS LAN

Developed by the School of Textile and Fiber Engineering, the GTWM [60] provides a versatile framework for incorporation of sensing, monitoring and information processing devices. Shown in Figure 41, the GTWM is a wearable garment (vest) that can be used to monitor the vital signs of humans in an unobstructive manner. The vest functions like a motherboard, with plastic optical fibers and other specialty fibers woven throughout the actual fabric of the shirt. The flexible data bus integrated into the structure transmits the information from the sensors mounted on the shirt. The bus also serves to transmit information to the sensors (and hence, the wearer) from external sources, thus making GTWM a valuable information infrastructure. The plastic optical fiber spirally woven into the structure can be used to pinpoint the exact location of a bullet penetration in combat causality care. Shirt is lightweight and can be worn easily by anyone – from infants to senior citizens.

The first step in unleashing the GTWM's potentials was to give it the ability to communicate with the outside world wirelessly. We have demonstrated the wireless communication of vital signs, in particular, electrocardiogram (ECG) signals (and audio) from the shirt over wireless local area (home) networks. Even though many other signals such as body temperature and respiration can be

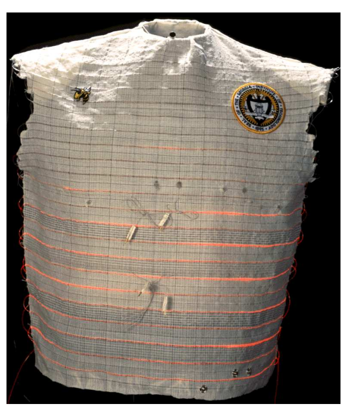


Figure 41: The Georgia Tech Wearable Motherboard

collected from the shirt, our research primarily focuses on ECG. This is because ECG poses a great challenge compared to many other vital signals due to the weakness of the signal from the sensors and environmental noise effects. Moreover, it is one of the most important vital signs of the human body.

We designed and tested an end-to-end wireless system that demonstrates real-time transmission and monitoring of ECG signals acquired from the shirt on a remote station. The ability to communicate the information wirelessly will unleash GTWM's potentials in telemedicine, infant care (e.g., prevention of Sudden Infant Death Syndrome), elderly and post-operative care, and monitoring of astronauts, athletes, law enforcement personnel and combat soldiers. By making the user completely tetherless, and providing the ability to perform computation/storage remotely, the GTWM can be used in continuous study of the user, with new applications in context-aware computing, affective computing and personal information processing.

A.1 Wireless Communication of Vital Signs Over a Wireless LAN

The overall system is shown in Fig. 42. The system consists of several stages:

- The GTWM, which provides the framework for collecting sensory information from the body.
- A signal conditioning unit to process the signals from the sensors by amplification, filtering, etc.
- A data acquisition unit to digitize the signals and read them into the portable computer/transmission device.
- Wireless modems to transmit the digital data.
- Computation and storage capabilities in order to collect and analyze the data.
- User interface including graphics and sound.

The GTWM was used as a personal area network, collecting information from the sensors (electrodes) on the body and delivering them to our signal conditioning unit.

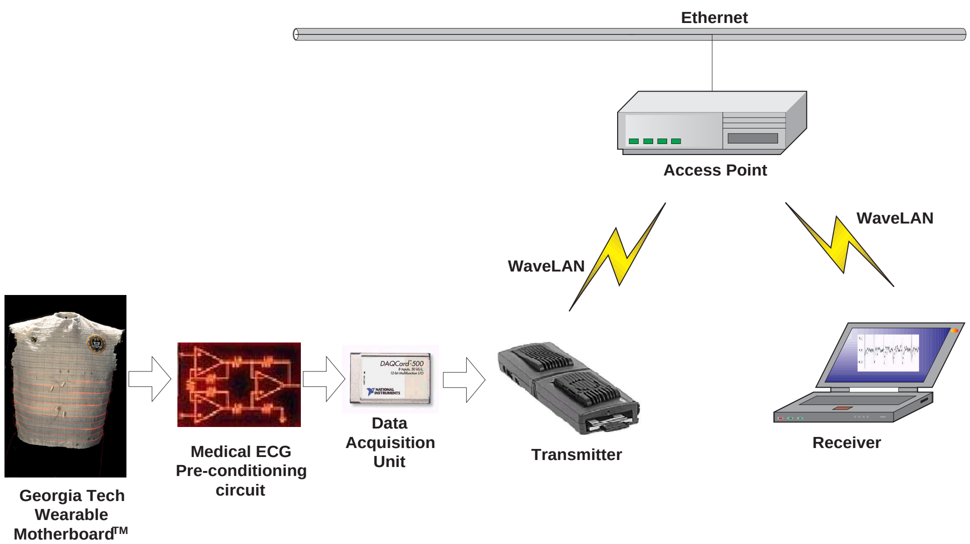


Figure 42: System Overview for Wireless Transmission of ECG from the GTWM

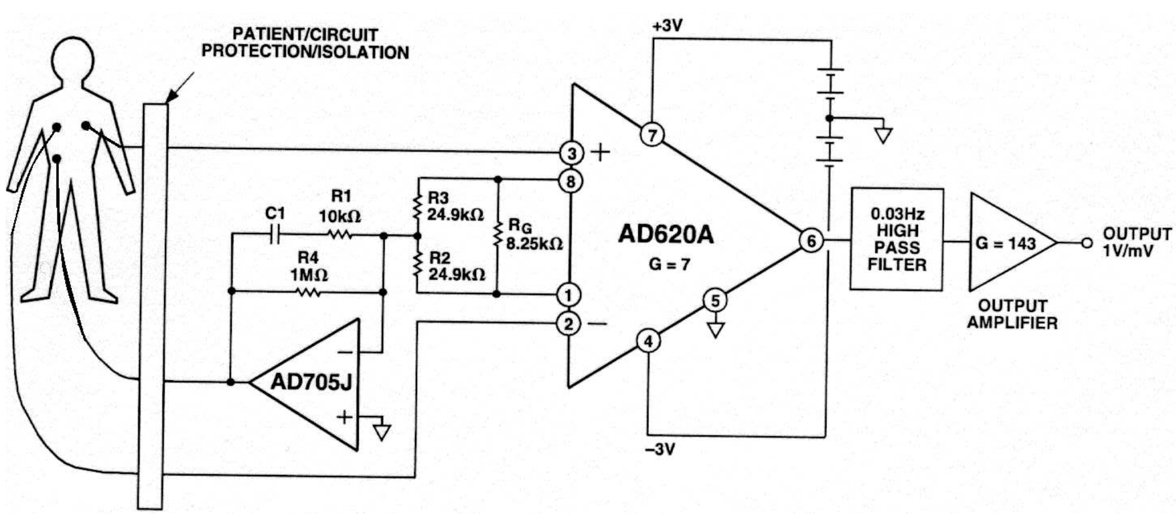


Figure 43: Medical ECG Preconditioning Circuit

The electrical activity of the human heart, although detectable on the body surface, is quite weak in magnitude (about 1 mV) and subject to environmental and biological noise and artifacts. A three-electrode ECG circuit, shown in Figure 43 [61], was built to amplify the electrical signal from the heart and reject environment noise and artifacts. The signals going to nodes 2 and 3 in the figure were differentially amplified, producing the ECG signal. A reference to the circuit common was established via a third reference electrode (shown as connected to the abdominal area). This node is not at absolute ground and has a non-zero potential that is common to both amplifier inputs, and must be rejected. A high pass filter was used to block DC and low frequencies due to motion artifacts. Analog Devices' AD620 Low Power Instrumentation Amplifier was used, which offered low noise, low input bias current, and low power usage [61].

Data acquisition was achieved by using National Instruments' NI-DAQ 500 card. It has a 12-bit analog to digital convertor (ADC) with analog signal resolution of 2.44mV in the +5V range and an aggregate acquisition rate of up to 50 k Samples/s. This was more than adequate for our ECG and voice signals and was able to support a number of other signals as well. The details of our sampling decisions can be found in [62].

We used WaveLAN modems, operating based on IEEE 802.11 standard, to transmit the information wirelessly. Two WaveLAN access points (base stations) were used to cover the aware home. A wearable personal computer (belt PC) was used as our central processor. The belt PC was a small, lightweight, battery operated PC with all the functionalities of a regular PC, and could be worn as a belt on top of the shirt to create a tetherless system. As wearable computers are becoming more and more common, any PC 104 [63, 64] system could be used, or in the final product, the belt PC could be replaced with a tiny transceiver unit. Windows sockets [65], which is an open interface for networking programming under Microsoft Windows, was used as the network application programming interface (API). Each of our programs (at the server and client sides) was a single executable code, complete with graphical user interface (GUI).

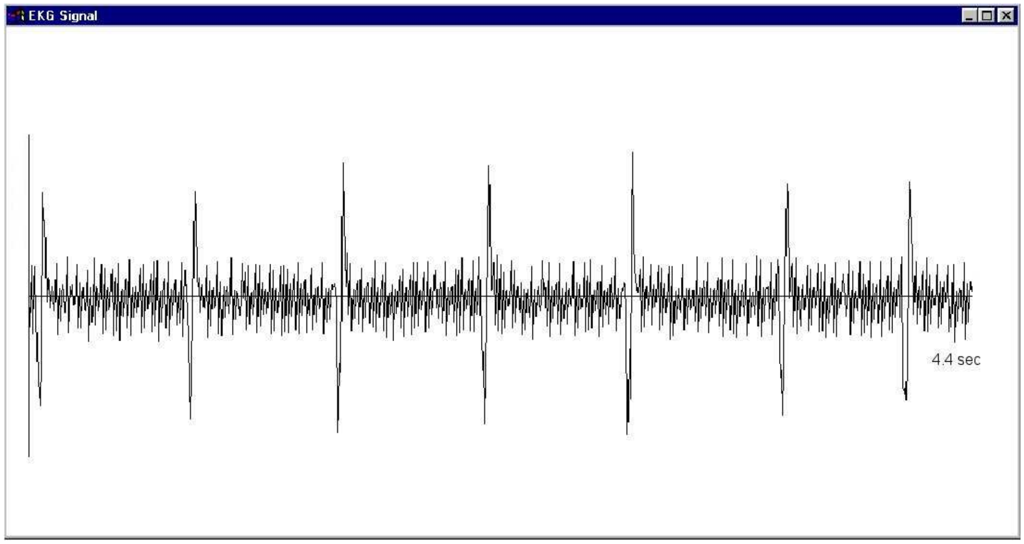


Figure 44: Received ECG Trace

ECG data packets were transmitted at every tenth of a second, at a rate of 12.8 kbps. Higher sampling rates (and/or higher redundancy) is recommended, in order to provide more reliability in error-prone wireless channels. Audio from a small tie-clip microphone on the shirt was successfully transmitted and reconstructed (played back), at 8000 samples per second, interleaved (time multiplexed) with the ECG data. The quality of the audio signal was good, however, it suffered from a small delay since we buffered some of the audio at the receiver in order to guarantee a better-quality audio. Successful transmissions of the ECG waveforms with signal-to-noise ratios as low as 5 dB were demonstrated within the aware home. Clear readings were obtained within the coverage area of the wireless-LAN which included the house in its entirety. The received signal was plotted in real-time on the remote station's monitor. A received ECG trace for a period of 4.4 seconds is shown in Fig. 44. Since the base stations are connected to the Internet, the user's signals can essentially be monitored from anywhere in the world.

The system was very easy to use (plug and play) and most of the activities were transparent to the user. By adding the real-time wireless capabilities, the GTWM has become an extraordinary tool within the house. The wireless GTWM has unique applications in telemedicine, human-computer interaction (HCI), and personal information processing (PIP) [66]. More information about our research could be found in [62].

APPENDIX B

ISO AND ITU COMPRESSION STANDARDS

B.1 Audio coding Standards

A number of audio coding standards are listed in Table 9. For example, MPEG-1 consists of three operating modes, referred to as layer-1, layer-2, and layer-3, which provide different performance/complexity trade-offs. MPEG-1 layer-3 (more commonly known as ”MP3”) is the highest quality mode and was designed to operate at about 128 kbps for stereo audio. MPEG-2 advanced audio coding (AAC) provides improved audio compression performance compared to MP3, as well as improved coding of stereo and multichannel audio signals. MPEG-4 addresses new functionalities, ranging from low-bit rate speech to high-quality multichannel audio.To code natural audio, MPEG-4 uses a number of codecs, including parametric coder for 2-4 kbps speech at 8-kHz sampling rate or 4-16 kbps audio at 8- or 16-kHz sampling rate, CELP coder for speech at 6-24 kbps at 8 or 16 kHz for narrowband and wideband speech, respectively, and MPEG-4 AAC for general audio signals over a broad range of bit rates [1].

B.2 Image Coding Standards

Table 10lists a few of the current imaging compression standards. JPEG, named after the Joint Photographic Experts Group, is the most widely used image compression algorithm. It typically compresses a color (RGB) image with 24 bits/pixel by a factor of 24 to 48 corresponding to bit rates in the range of 0.5 to 1.0 bits/pixel [1].

Losless compression of images is very important in a number of applications, such as medical imaging and compression of non-natural images such as computer graphics. The JPEG-LS is designed to provide lossless compression of continuous-tone images. In addition, it includes a ”near-lossless” mode for applications that could tolerate a known maximum error for any given pixel value. Lossless compression of natural images typically achieves a compression ratio of less than 2:1; non-natural images such as computer graphics can achieve much higher compression rates.

JPEG-2000 is designed to provide improved compression performance, various forms of scalability (e.g., bit rate scalability, spatial resolution scalability, and SNR scalability), and support for high bit rates up to lossless compression, and error resilience [1].

B.3 Video Coding Standards

Current video compression standards are listed in Table 11 [1]. Currently, the video compression standards mostly used for video communication are H.263 V2, MPEG-4, and H.264/MPEG-4 part 10 AVC [1].

The ITU H.261 was designed for video conferencing over integrated services digital network (ISDN) and operates at p x 64 kbps where p = 1,2, , 30. H.263 was designed for video telephony over public switched telephone network (PSTN) and supports 33.6 kbps and higher. The Moving Pictures Expert Group (MPEG) standards were developed to compress video and audio for different uses.

MPEG-1 was designed for video on digital storage media (CD-ROM) and achieves approximately VHS quality video and audio at about 1.5 Mbps. MPEG-2 was designed for digital television and supports bit rates of 2-20 Mbps. MPEG-2 is the basis of the standard for the video portion of digital television (DTV) and high-definition television (HDTV) in most of North America, Europe and Asia. MPEG-4 was designed to provide improved compression efficiency and error resilience as well as other functionalities such as content-based interactivity. The newest video compression standard, known as H.264 or MPEG-4 Part 10 AVC achieves a significant compression over all prior video coding standards and can support anywhere from 10s of kbps to 10s of Mbps, depending on the application [1].

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